Rodent Pests and their Control

2nd Edition

Edited by

Alan P. Buckle and Robert H. Smith

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Alan P. Buckle

School of Biological Sciences, University of Reading, UK

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School of Applied Sciences, University of Huddersfield, UK

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CABI
Nosworthy Way
Wallingford
Oxfordshire OX10 8DE
UK

Tel: +44 (0)1491 832111
Fax: +44 (0)1491 833508
E-mail: info@cabi.org
Website: www.cabi.org

CABI
38 Chauncy Street
Suite 1002
Boston, MA 02111
USA

Tel: +1 800 552 3083 (toll free)
E-mail: cabi-nao@cabi.org

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Contributors

S.A. Battersby, Robens Centre for Public and Environmental Health and Environmental Regulatory Research Group (ERRG), University of Surrey, Guildford, GU2 7XH, UK.

A.P. Buckle, Vertebrate Pests Unit, School of Biological Sciences, University of Reading, Harborne Building, Whiteknights, Reading, RG6 6AS, UK.

D.P. Cowan, National Wildlife Management Centre, Animal Health and Veterinary Laboratories Agency (AHVLA), Sand Hutton, York, YO41 1LZ, UK.

C.T. Eason, Centre of Wildlife Management and Conservation, Lincoln University, Lincoln 7647, Canterbury, New Zealand.

M.W. Fall, National Wildlife Research Center, USDA Animal and Plant Health Inspection Service, Wildlife Services, 4101 LaPorte Avenue, Fort Collins, CO 80521, USA (retired).

M.G.P. Fenn, Syngenta Crop Protection AG, Schwarzwaldallee 215, Basel 4002, Switzerland.

L.A. Fiedler, National Wildlife Research Center, USDA Animal and Plant Health Inspection Service, Wildlife Services, 4101 LaPorte Avenue, Fort Collins, CO 80521, USA (retired).

R.J.B. Flor, International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines.

M. Gelling, The Recanati-Kaplan Centre, Wildlife Conservation Research Unit, Department of Zoology, University of Oxford, Tubney House, Abingdon Road, Tubney, Abingdon, OX13 5QL, UK.

G. Howald, Island Conservation, 2161 Delaware Ave., Suite A, Santa Cruz, CA 95060, USA.

R.A. Johnson, Vertebrate Pests Unit, School of Biological Sciences, University of Reading, Harborne Building, Whiteknights, Reading, RG6 6AS, UK.

D. Kaukeinen, 2317 Paulwynn Road, Wilmington, DE 19810, USA.

M. Lund, formerly of Danish Pest Infestation Laboratory, Faculty of Agricultural Sciences, Institute of Integrated Pest Management, Forsøgsvej 1, DK-4200 Slagelse, Denmark (deceased).

D.W. Macdonald, The Recanati-Kaplan Centre, Wildlife Conservation Research Unit, Department of Zoology, University of Oxford, Tubney House, Abingdon Road, Tubney, Abingdon, OX13 5QL, UK.

A.N. Meyer, Acheta, Garden Cottage, Horsemoor, Chieveley, RG20 8XD, UK.

H.-J. Pelz, Vertebrate Research Group, Institute for Plant Protection in Horticulture and Forests, Julius Kühn-Institut – Federal Research Centre for Cultivated Plants, Toppheideweg 88, 48161 Münster, Germany.

M.G. Pereira, NERC Centre for Ecology & Hydrology, Lancaster Environment Centre, Bailrigg, Lancaster, LA1 4AP, UK.

C.V. Prescott, Vertebrate Pests Unit, School of Biological Sciences, University of Reading, Harborne Building, Whiteknights, Reading, RG6 6AS, UK.

E.D. Potter, NERC Centre for Ecology & Hydrology, Lancaster Environment Centre, Bailrigg, Lancaster, LA1 4AP, UK.

J. Ross, Faculty of Agriculture and Life Sciences, Lincoln University, Lincoln 7647, Canterbury, New Zealand.

G.R. Singleton, International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines.

R.F. Shore, NERC Centre for Ecology & Hydrology, Lancaster Environment Centre, Bailrigg, Lancaster, LA1 4AP, UK.

F.J.L. Smit, Dutch Society for the Protection of Animals, Scheveningseweg 58, PO Box 85980, 2508 CR, The Hague, The Netherlands.

R.H. Smith, School of Applied Sciences, University of Huddersfield, Huddersfield, HD1 3DH, UK.

M.G. Townsend, National Wildlife Management Centre, Animal Health and Veterinary Laboratories Agency (AHVLA), Sand Hutton, York, YO41 1LZ, UK.

L.A. Walker, NERC Centre for Ecology & Hydrology, Lancaster Environment Centre, Bailrigg, Lancaster, LA1 4AP, UK.

B.J. Wood, Merrivale Research, Exton Lane, Exton, Exeter, EX3 OPP, UK.

Preface

From comments that we have received, it seems that the first edition of this book was welcomed when it was published in 1994 – by both those studying and those practising rodent pest management. The concept of a book that combined information from the latest scientific research with advice about the practical implementation of pest management programmes appears to have been a good one. Therefore, the basic plan of the original book has been retained.

This is not a fast-moving branch of science and there was never an urgent need to bring forward another edition. Eventually though, we were persuaded that enough had changed, and sufficient new information had accumulated, to make a second edition worthwhile after an interval of 20 years.

We began the task of producing this edition several years ago, but pressure of work on us both, and commitments in our personal lives, have meant that progress has been much slower than we wanted. So we should first express our grateful thanks to those authors who diligently met the initial submission deadlines and then waited (mostly) with great patience to see the book finally come into print. We are also grateful to those authors who needed more time, and more encouragement, to complete their allocated chapters, having recognized from our own lives the difficulties of finding time to do the necessary work. Indeed, without all of the authors, we would have no second edition.

In producing this new edition we have taken the opportunity to add some additional chapters and substantially to modify others. The humaneness of vertebrate pest control interventions has come to greater prominence since the publication of the first edition and a chapter on this is now provided. The important issue of the presence of residues of anticoagulant rodenticides in wildlife is also recognized with a chapter on that subject. The use of rodenticides for the removal of rodents as detrimental alien invasives in island ecosystems was in its infancy at the time of the first edition, but has since become a major aspect of practical wildlife conservation on a global scale. Preeminent scientists in all of these areas have contributed to the new edition. It is satisfying that, once again, these new chapters combine up-to-date scientific research with highly practical advice to practitioners.

We thank the CAB International staff, Alex Lainsbury and Rachel Cutts, whose patience must have been sorely tried many times, but whose support and encouragement were never less than exemplary.

Finally, we wish to remember the authors from the first edition who have died since its publication: Norman Gratz, John Greaves and Mogens Lund. All of these men made significant contributions to the study and development of rodent pest management in their lifetimes. The book's first edition, as well as their published literature, stand testament to these contributions and to their scientific standing. Their knowledge and experience were much missed in the preparation of this new edition, and our thanks go to those other authors who stepped in to help us with the important chapters that they contributed to the first edition.

Alan Buckle
Robert Smith
March 2014

1 The Natural History of Rodents: Preadaptations to Pestilence

D.W. Macdonald,[1] M.G.P. Fenn[2] and M. Gelling[1]
[1]*The Recanati-Kaplan Centre, Wildlife Conservation Research Unit, University of Oxford, Tubney, UK;* [2]*Syngenta Crop Protection, Basel, Switzerland*

Introduction

The Rodentia make up over 40% of mammal species and represent the largest order of mammals, comprising some 2277 species in 30 extant families that include 481 genera (Wilson and Reeder, 2005). A further 12 families and 300 genera are known only from fossils. Their principal unifying feature is the possession of one pair of incisors above and below and the use of these for gnawing. Over the past two decades, as taxonomists continue to develop techniques with which to describe rodent phylogeny, so there has been much debate as to their monophyletic origin. Cladistically based morphological analyses and molecular analyses provide phylogenies that are not in total agreement; there is strong evidence for several monophyletic groups, but also support for the premise of recurrent independent evolution of some features, notably the zygomasseteric system and lower jaw (Honeycutt *et al.*, 2007) (see Fig. 1.1).

The name of the order is derived from the Latin *rodere*, meaning to gnaw. Rodents' incisors are remarkable both in their length – with the open roots of the lower pair reaching back almost to the articulation of the jaw – and in their structure – with only the front surface being coated with enamel (cf. lagomorph incisors, which are encircled by enamel). This enamel wears less quickly than the softer dentine behind, thus producing a self-sharpening blade. There is a gap, the diastema, between the incisors and the rest of the dentition. The number and appearance of the cheek teeth vary widely between species.

The first rodents, called the Paramyidae, arose about 60 million years ago (mya) in the late Palaeocene from an insectivore-like ancestor. The most ancient surviving lineage is *Aplodonta*, the American mountain beaver. Contemporary rodents are mostly small, the largest being the capybara, *Hydrochaerus hydrochaeris*, at *c.*50 kg. Some extinct forms were much larger, such as *Castoroides*, a 200 kg bear-sized beaver, and the Pliocene rhino-sized capybaras.

The musculature and shape of the skull reflect phylogeny and function. The majority of rodents are seed eaters, but some are insectivorous and some are versatile omnivores. Rodents are classed into three suborders, based on the working of the bone–muscle pulley systems of their jaws (Fig. 1.2). The primitive arrangement is called squirrel jawed (sciurognathus), in which the chewing (masseter) muscle drops vertically from the cheek (zygomatic) arch of the skull to a bony flange behind and below the teeth on the lower jaw. This flange is similar in the squirrels (suborder

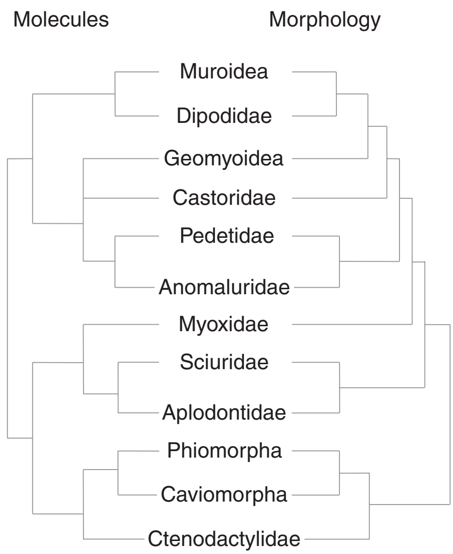

Fig. 1.1. Rodent phylogeny (with permission from Honeycutt *et al.*, 2007), describing different results obtained from morphological (Marivaux *et al.*, 2004) and molecular (Nedbal *et al.*, 1996; Adkins *et al.*, 2001; Montgelard *et al.*, 2002: DeBry, 2003) data.

Sciuromorpha) and mice and rats (suborder Myomorpha), but it is angled outwards in the more recent porcupine-jawed (hystricognathus) rodents such as porcupines and cavies (suborder Hystricomorpha). These structural differences between the suborders mirror functional differences in their gnawing action.

The squirrel stock arose in the late Oligocene (37–25 mya) and is now found on every continent except Antarctica and Australia. The myomorph jaw is more modern, and tends to have fewer molars (three, two or even one on each side) than do other rodents. For example, the dental formula of the brown rat is: 1/1, 0/0, 0/0, 3/3 = 16. The earliest myomorphs, like *Paracricetodon* of the Oligocene, had molar cusps linked by ridges that foreshadow the modern grinding arrangement characteristic of voles. In the late Miocene (24–25 mya), there were three explosive myomorph radiations.

1. In less than 2 million years, more than 350 species of New World mice (Sigmodontinae, sometimes called Hesperomyinae) spread throughout the New World from North America, while the hamsters (Cricetinae) spread through the Palaearctic. Many retained cuspid teeth.
2. A niche for diminutive grazers was made possible by the evolution of grasses in the late Miocene and this was occupied by voles (a subfamily known as Arvicolinae or Microtinae), which arose in the late Pliocene (5–2.5 mya) from the hamster lineage. The 100 or so extant species of vole owe their success to teeth on which the enamel forms a pattern of grinding zigzags atop wide and high crowns (hypsodont teeth) with parallel sides (prismatic). In many species, the roots of these teeth remain open throughout their lives to allow continuous growth.
3. The true rats and mice (subfamily Murinae) probably arose in South-east Asia in the late Miocene and have an omnivorous, but largely vegetarian, diet. Their food is prepared for digestion on the low-crowned cusps of rooted teeth. Their fossils were rather uncommon until the late Pleistocene but they were almost certainly abundant and diverse in Africa, southern Asia, New Guinea and Australia long before that. In the late Pleistocene, in company with early humans, some murines (such as rats, *Rattus* spp., and mice *Mus* spp.) radiated worldwide.

Contemporary murines number more than 560 species (Wilson and Reeder, 2005). Human association with commensal rodents is truly ancient: bones of rodents of the genera *Mus* and *Rattus* are found alongside those of humans in mid-Pleistocene (1–2.5 mya) encampments.

The classification of these myomorphs remains highly volatile. Here we have treated them all as subfamilies of the all-embracing Muridae (following Wilson and Reeder's 2005 *Mammal Species of the World: A Taxonomic and Geographic Reference*).

The success of the myomorph radiations had a major effect on the dynamics of ecosystems such as the tundra and steppe, and on their predators – among the Carnivora, they stimulated a radiation of long, thin, burrow-hunting Mustelidae. Rodent predation on the seeds of forest trees has

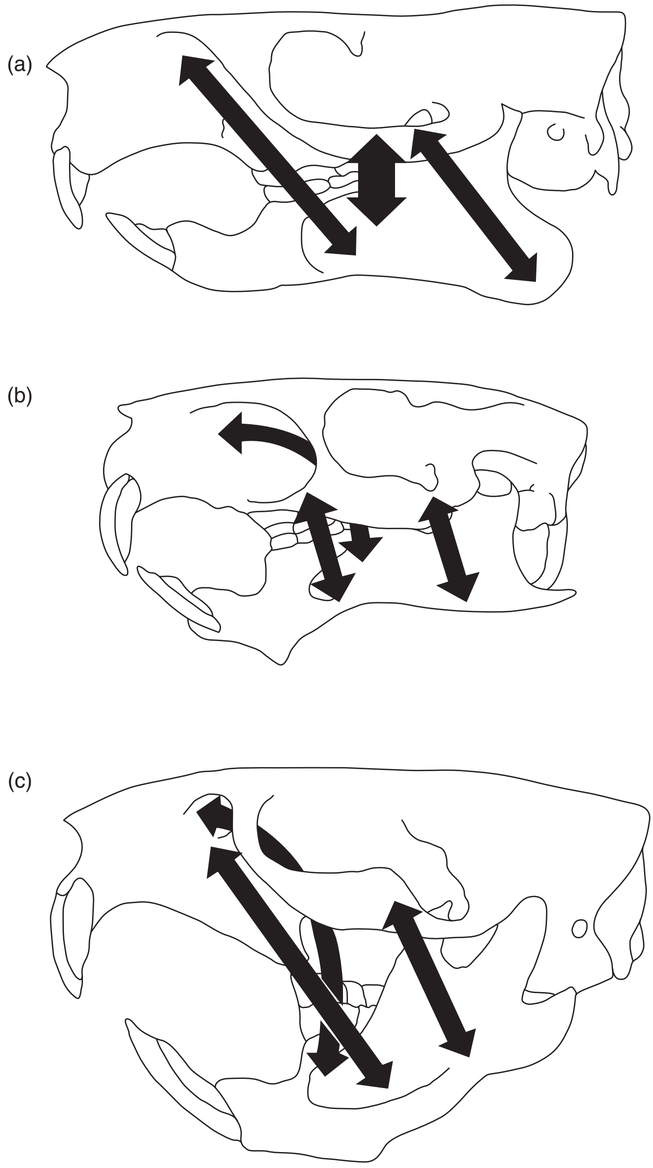

Fig. 1.2. Jaw musculature of suborders of rodents: (a) primitive squirrel-jawed arrangement (sciurognath); (b) arrangement in mice and rats (myomorphs) and advanced squirrels (sciuromorphs); (c) more recent porcupine-jawed arrangement in porcupines and cavies (hystricomorphs). The arrows indicate the position of the muscles. The chewing muscle drops vertically in (a), but is increasingly angled outwards through (b) and (c).

probably contributed to the evolution of erratic fruiting (masting) in both temperate and tropical forests, and the reproductive strategies of forest rodents must now cope with masting.

Finally, the porcupine-like rodents have Old and New World lineages, the former first known from Egypt about 30 mya. They tend to retain four molars in each jaw, each low-to-medium crowned with three to five transverse ridges. The taxonomy of rodents is complicated and controversial, and the foregoing is a very simplified summary. Dental evidence of phylogenetic relationships can be found in Marivaux *et al.* (2004), and molecular evidence in Adkins *et al.* (2001), DeBry (2003), Montegelard *et al.* (2002) and Nedbal *et al.* (1996). A general account of the natural history of the order is given in Macdonald (2009), and of their evolution in Honeycutt *et al.* (2007).

Rodents vary enormously in morphology. They range in size from the pygmy mouse, *M. minutoides*, which weighs about 5 g, to the capybara, *Hydrochaeris hydrochaeris*, which can exceed 50 kg. The rodent stomach can range from a simple sac in the dormice (Gliridae – the only rodents without a caecum) to the complex ruminant-like organ of the lemmings (*Lemmus* spp.).

Physiology can be adapted to suit the desert life of the gerbils (e.g. *Gerbillus* and *Tatera* spp.) or the aquatic habits of the coypu, *Myocastor coypus*, and European beaver, *Castor fiber*. The squirrels (Sciuridae) include highly arboreal species, and several members of this family, along with dormice (Gliridae) and birch mice (Zapodidae), hibernate (edible dormice – eaten by the Romans – hibernate for 7 months of the year).

Life history strategies can be short and prolific, as in the *r*-selected house mouse, *M. domesticus*, or long with low fecundity as in the *K*-selected African spring hare, *Pedetes capensis*, which only produces a single young each year, and also lays claim to the largest ears in the rodent world (Hanney, 1975) (see next section for explanations of these selection terms). In adaptation to their ecological circumstances, rodent social systems embrace monogamous water voles, *Arvicola amphibius*, polygynous wood mice, *Apodemus sylvaticus*, family groups of Alpine marmots, *Marmota marmota*, herds of capybara and a blend, apparently unique among mammals, of monogamy and communal denning in the mara, *Dolichotis patagonum*. They also exhibit dramatic intraspecific variation, such as the contrasting niche and social organization of terrestrial and aquatic populations of water voles. Rodent breeding systems include such phenomena as the single-sex litters of wood lemmings, *Myopus schisticolor*, and the manipulated sex ratio of coypus caused by selective abortion of male-biased litters by females in poor condition (Gosling, 1986). Naked mole rats, *Heterocephalus glaber*, are unique among mammals in the degree of their eusociality (Jarvis, 1981) with only one female breeding within the group. Evolution of eusociality is likely to have evolved from a monogamous mating system where cooperative brood care was already established (Burda *et al.*, 2000).

Added to the diversity within the order are the adaptability of many individual species and the behavioural flexibility of individuals. Thus, brown (or Norway) rats, *R. norvegicus*, and house mice can be found throughout the world, using their generalist body plan to feed and breed wherever humans go, and their sophisticated behaviour patterns to avoid the most cunning and increasingly sophisticated attempts at eradication.

Brown rats and house mice, along with the roof rat, *R. rattus*, are known as commensal rodents, meaning that they are usually found in association with people, 'sharing the table' (*mensa*: a table, in Latin). However, as the word commensal implies no damage to the host, these rodents might more precisely be termed kleptoparasitic. Because of this and because of the importance of the first two species in medical and experimental psychological research, knowledge of rodent biology is heavily biased by an overwhelming emphasis on commensal rodents. There remains within the literature a significant bias towards laboratory studies; a survey of the science citation index between 1986 and 1988 revealed 23,700 publications on rats; from 2008 to 2010 this had risen to over 99,000. Nonetheless, the proportion of studies on wild rats has increased from fewer than 12 in the period 1986–1988, to 2056 in 2008–2010, over 10% of which were studies conducted in the wild.

Apart from sight, which is poor in the majority of rodent species (blind rats and mice appear to survive adequately; Meehan, 1984), rodents generally have very acute senses, and smell, hearing, touch and taste are well developed. Social odours play an enormous role in rodent biology, both through a direct impact on behaviour and through the physiological impact of primer pheromones (reviewed in Johnston, 2003). Functional odours are produced in the urine and faeces, and in secretions from apocrine and sebaceous glands (e.g. flanks, prepuce, eyes). Some species respond innately to the odour of predators, and laboratory studies of rats and mice reveal an ability to discriminate conspecifics differing at only one locus (e.g. Brown *et al.*, 1991). Scent marking plays an important role in territoriality in many species, and territoriality can affect rodent control. House mice have such a highly developed system of scent marking that it enables them to find their way in total darkness. Mice live in territorial family groups in which a breeding pair and their adult offspring all mark extensively with urine. This network of marks coats every object in their environment; it allows them to negotiate narrow bridges in total darkness, and to sense precipices through their noses. They create olfactory stalagmites up to 3 cm tall, which arise where repeated urinations bind with dust. These are marked especially by the dominant male and breeding female. It seems they serve to announce the presence of the territorial animals to their offspring and their neighbours, the males broadcasting their dominance, the females their breeding status.

Olfaction is also important in transferring information between individuals and can affect rodent control. Taste, mediating food preferences and recognition, affects the efficacies of poison baits. The inability of rodents to taste certain compounds at a concentration that is abhorrent to humans (e.g. Bitrex® – denatonium benzoate) is used to 'safen' modern rodenticide baits. Many rodents produce ultrasounds (i.e. sounds above the normal level of human hearing, 20 kHz), which are apparently relevant in courtship and aggression, in eliciting parental care, as alarm signals and, possibly, in echolocation. Sounds in the 'audible' frequencies are also used for these purposes. Hearing is often the first sense to detect the approach of a potential predator; the most extreme case is the middle ear of desert-living kangaroo rats (Dipodidae), which amplifies the movement of the eardrum 92 times, compared with 18 times in humans, meaning that their hearing is four times more acute than ours (Webster, 1965).

Touch is a highly developed sense in many rodents: rats and mice with trimmed or removed vibrissae (whiskers) become subordinate when grouped with intact conspecifics. Tactile hairs are found all over the pelage and are important in ensuring that the rodent moves in close proximity to vertical surfaces, a behaviour that may limit the possible avenues of attack of predators. Closely related to the sense of touch is that of 'muscle awareness' or kinaesthesis, by which a rodent is aware of its physical environment through a combined memory of movement and touch. This is vital for quick escape from predation, where a rodent will run along a 'prerecorded' path at great speed.

Rodents are often superb athletes. The roof rat can walk a 'tightrope' along telephone wires to reach food, a skill that makes circular rat guards necessary on ships' hawsers in many ports. The brown rat can swim for 72 h non-stop and has been known to enter houses through lavatory U-bends. Commensal rodents can climb brick walls with comparative ease. Other species are accomplished jumpers, with the African spring hare covering 2 m in a single bound. Flying squirrels have a gliding membrane on each side of the body, and one species has been observed to use flapping movements to reach a point that was 1 m higher than its launch pad, and to glide a horizontal distance of 135 m (Hanney, 1975). A rat or mouse can generally enter any orifice through which its head will fit, with young mice being able to enter a gap less than 10 mm high (Meehan, 1984).

Running through this awesome diversity of traits – small size, acute senses, dietary opportunism, athleticism and nocturnality – it is clear that these characteristics combine to predispose a minority of rodent species to be pests. However, it is in their population processes that this predisposition is most clearly seen.

Population Processes and Demography

Some environments favour species with a capacity to breed explosively. In unpredictable environments, such as where trees mast, the supply of resources may exceed the demand for them, as the survivors of a period of stricture find themselves in a land of plenty as conditions improve. Similarly, in an ephemeral environment, the first immigrants may be free of shortages. Their reproductive success is then unrestrained by their competitive ability or by population density. There will be plenty to go around and the best way to capitalize upon it is to produce lots of young as fast as possible while the going is good (and to produce plenty of emigrants before the going gets bad). This sort of environment is called *r*-selecting, and species whose lives follow this pattern are said to have been *r*-selected by evolution (the name, *r*, comes from the logistic equation where *r* describes the potential for population increase). Rodents such as the microtine voles and murine rats and mice are *r*-strategists, with explosive reproductive rates and, at least intermittently, very high population densities but often poor individual survival.

In contrast, animals in a stable or seasonally predictable environment will utilize every nook and cranny. In these circumstances, supply and demand will be more in balance, and populations will be limited by the availability of food and other resources. The only way to prosper relative to competitors is to secure a larger slice of the available resource cake, and this puts a premium on individual prowess. Under these circumstances, the emphasis is on quality and not quantity. Parents will secure more descendants in the long run if they invest heavily in a smaller number of offspring, cosseting each one as they groom it for entry into the competitive affray. Equally, the young are heavily dependent on their parents' competitive ability, so parents under these circumstances must also invest heavily in their own muscle power. Such species are said to be *K*-selected (*K* referring to the carrying capacity of the environment, also from a logistic equation). *K*-selection promotes individual success under conditions where individuals are living in a population at or near to the carrying capacity of its environment.

In both the *r* and *K* cases, the rewards – maximum lifetime reproductive success – are the same, but the tactics for competing are different due to the different circumstances. Under boom-or-bust (*r*-selecting) circumstances faced by voles and lemmings, it is crucial to produce offspring today in case there is no tomorrow, and so it is advantageous to breed prolifically while young even if doing so leads to premature death and so lowers the possible lifetime score. Small size can be a means to achieve mass production, favouring many undeveloped young over fewer precocial young. Small body size demands a high metabolic rate to compensate for an unfavourable surface to volume ratio. A high metabolic rate results in faster growth and accelerated reproduction. Some rodents have even faster metabolisms than would be predicted from their size, apparently to adapt them to extremely *r*-selected lifestyles. The high metabolism of a female Norway lemming, *Lemmus lemmus*, enables her to have her first dozen offspring by the time she is 42 days old. To achieve this her metabolism races in comparison with that of the comparably sized, but relatively *K*-selected, wood mouse, *A. sylvaticus*, which, with a conventional metabolism for its size, produces litters of four to seven young once or twice (maximum four times) a year. The demands for high productivity on the lemming are colossal, with their population peaks exceeding the troughs by 125-fold. A general introduction to this and related basic ecological topics is given by Begon *et al.* (1986).

It should be pointed out that the *r*–*K* distinction is a relative one: a brown rat is *r*-selected relative to a capybara, but *K*-selected relative to a field vole. The capybara's high productivity in comparison with that of domestic stock such as cattle makes it and various other large rodents excellent candidates for ranching (BSTID, 1991) whereas the rat's even higher productivity makes it a formidable pest.

Pest species tend to be *r*-selected. Most rodent pest species are small and extremely fertile. Many species become mature sexually at 2–3 months of age and the females produce litters of six or seven young after a short gestation period of 2–3 weeks. Further, the females are usually capable of post-partum oestrus, that is, they can become pregnant immediately after giving birth, and so another litter is produced as soon as the previous one is weaned.

Obviously, this maximization of reproductive process only occurs under favourable conditions, and it is the longevity of these conditions that determines whether logistic or irruptive population growth occurs (Fig. 1.3).

Logistic growth requires continuous favourable conditions (i.e. adequate food, water and harbourage). Under these circumstances, the population will reach a maximum level determined by intraspecific density-dependent factors such as competition for food or nesting sites. A good example is the stable conditions enjoyed by the Malayan field rat, *R. tiomanicus*, in oil palm plantations in South-east Asia (see Chapter 3).

Irruptive growth follows a similar initial pattern to that of logistic growth, with a slow start that rapidly accelerates into an exponential phase, but instead of approaching an asymptote the population suddenly

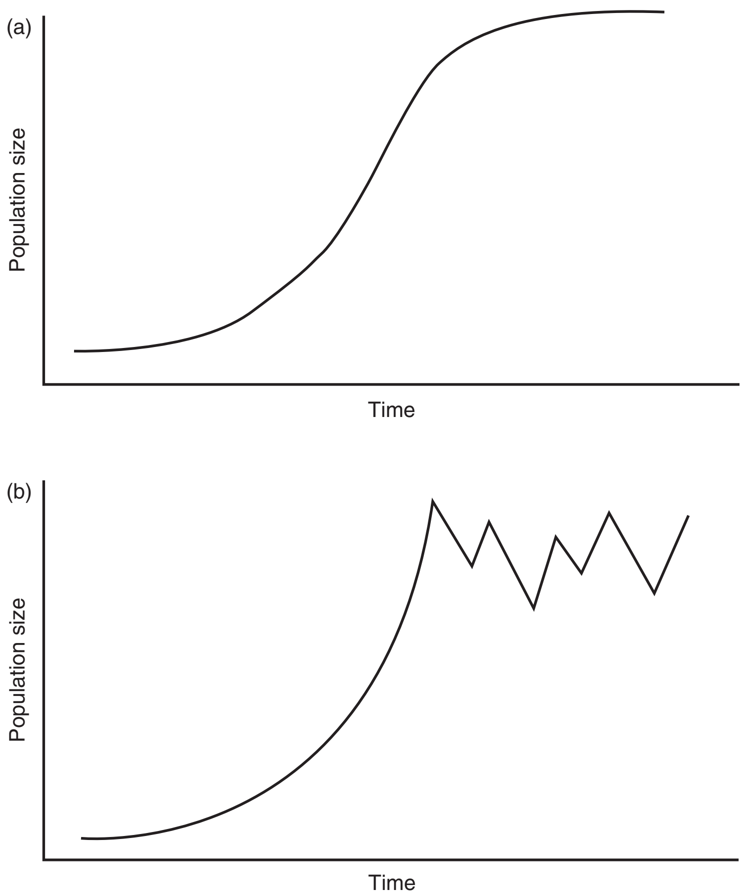

Fig. 1.3. A schematic representation of rodent population dynamics: (a) logistic growth; (b) irruptive growth.

crashes. This type of growth is characteristic of unstable or discontinuous favourable conditions. For example, environmental events such as above-average rainfall might increase the period and area over which high-quality food and/or harbourage are available, leading to an increase in both the length of the breeding season and the survival of individuals into the next season. The rodent population irrupts and the 'surplus' rodents travel out of their 'refuge habitats' and into previously unfavourable areas ('receptor habitats'). The crash comes when insufficient food is available in the following season to support the 'colonizers' in the receptor habitats and the population swiftly reverts to the level that can be supported from the refuges. Examples of such growth are the plagues of microtine rodents in Europe (e.g. *Microtus arvalis*) and the USA (e.g. *M. pennsylvanicus*), and of feral house mice (*M. domesticus*) in Australia, that are reliant on abundant ripening and early germinating seeds from early and harvest rains (White, 2002). Rodent population outbreaks, leading to severe food shortages in Mizoram (India), upland provinces of Laos and other sites in Asia are related to bamboo (*Melocanna baccifera*) masting. This type of bamboo is invaluable for farmers, but ecologically it is an aggressive species in which every 50 years or so each plant simultaneously flowers, sets seed and dies. In Laos, the most recent rodent outbreak has led to emergency food assistance being required for 85–145,000 people, as the primary crop of rice is an easy target for rats (Singleton *et al.*, 2010). Not only are pest species able to utilize food resources more efficiently, but they are also better able to breed under conditions of low diet quality and so have an advantage over species unable to breed until their diet quality is at a certain level, leading to the production of more litters, and thus to female offspring, throughout the year, thereby adding to the capacity of the species to remain a pest (Jackson and Van Aarde, 2004).

Although these different types of rodent population growth arise from the same basic reproductive potential (indeed *M. domesticus* can show either type, depending on the conditions), they pose markedly different management problems. Where logistic growth occurs, control measures (be they chemical, mechanical or ecological) must be sustained over the life of the crops, goods or structures that require protection. This is because the very existence of this type of growth indicates that conditions are continually favourable for the pest and must be regularly modified to make them unfavourable. Ideally, management aims to modify the carrying capacity of the environment for the rodent population to such a low level that the damage caused is economically insignificant. An example would be the removal of cut palm fronds from oil palm plantations during harvesting, resulting in a dramatic decrease in harbourage for *R. tiomanicus*. Unfortunately, in this case and many others, this sort of pre-emptive intervention is less economically viable than reliance on chemical rodenticides. However, even rodenticides are unlikely to be cost-effective unless pest managers are diligent in achieving near-complete control of the rodent population. This is because the shape of the logistic growth curve means that populations left with more than about 10% of their maximum numbers will quickly rebound to pest status. Indeed, the steepest part of the curve (i.e. where population growth is fastest) occurs at 50% of the asymptote, and consequently this is the target for reduction by culling in 'sustained yield harvesting' operations such as fisheries. Inefficient attempts at rodent pest 'management' can, as a result, produce more rodents, in total, than no control effort at all.

The management of irruptive rodent populations requires a different stratagem. As damage is confined to times of plague, sustained prophylactic control would be wasteful unless it cheaply forestalled irruptions (e.g. by habitat manipulation). Therefore, the management of irruptive rodent pests focuses on the prediction and monitoring of outbreaks, with the tactical and prophylactic use of rodenticides to nip the outbreak in the bud and so prevent a plague. An example of this approach is the PICA (Predict, Inform, Control, Assess) strategy for the control of mouse plagues in rural Australia (Redhead and Singleton, 1988).

The prodigious reproductive capacity of rodents has consequences beyond the design of control campaigns. It also means that predators are unlikely to be successful as biological control agents of rodent populations. The circumstances under which vertebrate predators can regulate prey populations are complex (Sinclair, 1989). However, in the context of predation as a means of controlling rodent pests, Southern (1979) drew the general conclusions that: (i) predators have no braking effect on an expanding population of prey; and (ii) their main impact is to delay the recovery of prey by keeping them at a lower level than they would otherwise reach. In some systems, predation may damp the food-driven oscillations in prey populations (e.g. Peterson and Page, 1988); they may also suppress the recovery of prey that have been decimated by other factors (Newsome, 1990). People are among the predators that may damp rodent population cycles, but socio-economic forces are diminishing this effect in some communities. In Morocco, gerbils, *Meriones shawi*, are rodent reservoirs of the protozoan disease zoonotic cutaneous leishmaniasis (ZCL). Gerbils were traditionally controlled by peasant farmers, but with the demise of rural communities this control is relaxed. Consequently, populations of *M. shawi* in Morocco tend to erupt and the prevalence of leishmaniasis in people soars (Petter, 1988). In many Middle Eastern countries the main reservoir of ZCL is the desert-adapted rodent *Psammomys obesus* (Ban-Ismail *et al.*, 1987). *Psammomys* has remarkable adaptations to feeding almost exclusively on the leaves of plants of the family *Chenopodiaceae*, but changes in land use and increased vehicular use have reduced the numbers of browsers, especially camels, which competed with the rodents for this forage plant. In addition, anthropogenic disturbance has been shown to enhance the occurrence of ZCL in Israel, which is positively associated with disturbed anthropogenic factors, water and the vector of ZCL (the sandfly, *Phlebotomus papatasi*) (Wasserberg *et al.*, 2003). Irruptions of *Psammomys* may also have been worsened by the widespread destruction of the raptors, jackals and foxes that prey on them. Controlling *Psammomys* is especially difficult because, as folivores, they do not eat seeds dressed in poison. One proposal has been to eradicate their food plants, or to replace them with competitors such as *Acacia* spp. Clearly, though, the ecological implications of such manipulations are unknown and potentially immense.

Land use change has far-reaching implications for many rodent populations, which, in order to survive within the landscape, must embrace rapid environmental change on both a spatial and temporal basis. There is an increasing array of literature available chronicling how rodents deal with and adapt to this change. For example, contrasting herbicide treatments on farmland result in different movement patterns of wood mice (Tew *et al.*, 1992). Furthermore, harvesting cereal fields results in an 80% decrease in resident wood mouse populations, largely through increased predation associated with the loss of cover (Tew and Macdonald, 1993). The presence of mice within this apparently homogenous landscape is, nonetheless, misleading; Tew *et al.* (2000) demonstrated that individual mice do in fact respond to the small-scale variations at a microhabitat level within the overall crop macro habitat. The mincing of mice in haymaking machinery may explain how horses become infected with trichinosis, which is caused by a nematode parasite that is normally transmitted from rodent to rodent and occasionally finds its way into their predators. In areas where agricultural practice confines the availability of habitat to discrete patches, the continuity of these patches through habitat linkages can provide not only corridors along which migration can occur, but also the sole habitat for some species; for instance, the presence of masting trees in hedgerows in pastoral Britain increases the local population size of small mammals able to live within the hedgerows (Gelling *et al.*, 2007).

Another consequence of the high reproductive rates of rodents under favourable conditions is the increase in turnover of generations, and the swift development of physiological resistance to anticoagulant rodenticides that this engenders. Indeed, rat and mouse populations in the UK may also have developed 'behavioural resistance' to rodenticides after decades of sustained selection pressure on rapid population growth.

Hence, the population dynamics of rodents determines their potential as pests and influences the strategy for their management. In addition to these general principles, the findings of research on many detailed aspects of rodent behaviour have a bearing on the tactics of management campaigns.

Social Organization and Behaviour

Some rodents, such as the greater or long-tailed pouched rat, *Beamys major*, are almost completely solitary, living in separate burrows and contacting the opposite sex just once each year. At the other extreme, the naked mole rats of eastern Africa are eusocial, with a social life reminiscent of that of termites (Jarvis, 1981). Only one female, the oversized 'queen', breeds at any one time, and she is mated by only two or three males. The rest of the colony, both males and females, are non-reproductive and act as workers (Sherman *et al.*, 1991). Increasing use of genetic analyses has shed new light on previously assumed social organizations. Microsatellite markers from the solitary, and considered monogamous, silvery mole rat, *Heliophobius argenteocinereus*, revealed that they are actually polygynous, with a heavily female-biased adult sex ratio. The large distances between burrow systems of mating partners suggests that the males might venture above ground in search of a mate, and the presence of a multiple-sired litter suggested that the mating system was more complex than previously considered (Patzenhauerova *et al.*, 2010).

A few rodent species, including the chinchillas (Chinchillidae) and the grasshopper mouse (*Onychomys*), as well as the beaver, seem to be monogamous. However, the majority of pest rodent species, especially the Muridae, are polygynous or promiscuous. The three cosmopolitan commensal species (*R. norvegicus*, *R. rattus* and *M. domesticus*) tend to form colonies that are probably loose agglomerations of small family units or 'clans' (Fenn and Macdonald, 1987), with a greater degree of tolerance within compared with between units. Excavations of brown rat burrows on landfill sites reveal that they are of the same general size and construction, regardless of their proximity to food and water sources, but that the burrows are more densely packed in more favourable locations (Lore and Flannelly, 1977). This suggests that the basic social unit of brown rat society remains relatively constant, but that the amount of territory defended by each clan varies inversely with the size of the whole colony. The results of several other studies support the contention that, under favourable conditions, large infestations of rodents will be composed of smaller groups, each defending a particular area.

Interestingly, the size of the subgroup or clan seems to be fairly constant across habitats, ranging from five to 20 individuals. Farhang-Azad and Southwick (1979) found the average size of a brown rat 'group' in the Baltimore Zoo (Maryland) to be 10.3 (range 11–19), whereas Leslie *et al.* (1952) found the average number of brown rats inhabiting an English maize rick to be 17. Calhoun (1963) allowed a brown rat population to build up over 27 months in a 10,000 ft^2 enclosure. The population increased from five pairs to a maximum of 180 individuals that were clearly divided into 11 discrete 'colonies', with an average of 10.6 rats per colony. House mice behave similarly, with a subgroup or 'deme' typically consisting of a dominant male, two to five females, up to three subordinate males and a number of juveniles (Reimer and Petras, 1967). The abundance, age structure and reproductive patterns of both *Mus* and *Rattus* populations do vary according to their habitat though, with shanty towns in Buenos Aires (Argentina) representing a more favourable habitat than city parkland (Vadell *et al.*, 2010). Male brown rats are organized into a dominance hierarchy, in which age is a better predictor of high status than is body weight, and dominance in multi-male societies, such as those of capybaras, affects mating success (Herrera and Macdonald, 1993).

Even after 200 generations in captivity, when released into a quasi-natural environment in the form of a large, outdoor enclosure, laboratory rats are able quickly to 'remember' innate 'wild' behaviours. On release, individuals are curious, but also cautious, and quickly investigate available shelter – a sensible precaution for prey species. On filming released laboratory rats for 6 months in this enclosure, Berdoy (2003) found that a colony was soon formed that quickly became a complex society, and that many problems these laboratory rats faced were resolved in ways similar to those used by their wild cousins. This adaptive ability ensures that commensal rodents are able to thrive in a wide variety of habitats.

The yellow-bellied marmot, *Marmota flaviventris*, occurs in rocky areas of the western USA in groups typically composed of one male and a harem of ten females (Armitage and Downhower, 1974), with a complex structure of social cohesion established according to age and kin (Wey and Blumstein, 2010). The black-tailed prairie dog, *Cynomys ludovicianus*, of central USA and northern Mexico forms towns containing up to 1000 individuals divided into clans or 'coteries', usually consisting of a male, three or four females and about six juveniles. Each coterie occupies a permanent territory that is handed down to succeeding generations (King, 1955). Living in such closely connected colonies has implications for gene dynamics; nevertheless, black-tailed prairie dogs avoid the adverse effects of inbreeding by social subdivision whereby polygynous mating behaviours and philopatric females ensure that inbreeding rarely occurs (Winterrowd *et al.*, 2009). Young beaver remain with their parents until they are about 2 years old, helping with the construction of dams and lodges. However, family parties of beaver never exceed 14 individuals (Hanney, 1975). Monogamous pairs of maras avoid each other for much of the year, but form an uneasy alliance to rear their young in a communal warren; the survival of young at the warren increases with the number of young present, perhaps because of the shared vigilance of their parents, milk theft and huddling for warmth (Taber and Macdonald, 1992).

The behaviour of dispersing individuals is vital to the establishment of new colonies and thus the reinvasion of controlled sites. Resource-based approaches are now increasingly being encouraged for rat population management; for example, using habitat management techniques to reduce rat populations. Home range sizes for rats living close to farm buildings are smaller than those of rats living in fields, and local habitat management focusing on cover and harbourage areas has been shown to have the potential to reduce Norway rat populations in and around farms (Lambert *et al.*, 2008). In contrast to the logistic populations that act as a reservoir of immigrants, irruptive plagues of mice or voles may appear to move out of their refuge habitat en masse and to advance into the receptor habitats. Whereas a farmer suffering a trickle of incursions by rats from a nearby rice field can do a lot to protect his stored grain by mechanical rodent proofing, encouraging the transient rodent to move on to easier pickings, the Australian wheat farmer is relatively helpless in the face of a mouse plague, which no amount of proofing on its own will exclude (Singleton and Brown, 1999).

Distance from a rodent focus is no guarantee of protection. Kozlov (1979) found brown rats in uncultivated areas up to 10 km from the nearest human habitation. Radio tracking on English farmland has shown that both brown rats and wood mice may regularly make nightly journeys of several kilometres, often from an outlying home site to a reliable food source (Fenn *et al.*, 1987; Hardy and Taylor, 1979; Tew *et al.*, 1992). Gosling and Baker (1989) found that most coypus studied in the wetlands of East Anglia (UK) remained within a couple of kilometres of their point of first capture, but that males ranged more widely, and that movements beyond the area reflected dispersal to new ranges, mainly by males.

As discussed earlier, in continually favourable habitats the logistical growth of populations of pest species will require regular containment, whereas irruptive populations require intermittent control that is timed to prevent an irruption. In both cases, understanding the social structure of the population is likely to facilitate balanced management. For example, in the case of *M. arvalis* in Bulgaria, groups of voles in burrow systems in non-crop habitats form the basis of the overwintering population, which may irrupt in favourable conditions the following year. When the burrow system count in these areas exceeds a certain threshold (5 burrows ha^{-1}, or about 25 voles ha^{-1}), the application of rodenticide directly into the burrows provides an effective and targeted means of prophylactic control. In many stable environments, what appears to the casual observer to be one 'infestation' of, say, brown rats may be a socially structured community. Thus, populations of brown rats are most effectively controlled by the use of large numbers of small bait points, probably because this type of distribution ensures that one or more bait points fall into the territory of each clan (Fenn and Macdonald, 1987). If a brown rat infestation did not contain such social subdivisions, then a small number of large bait points should be just as effective (especially with information transfer), but this is found not to be the case (Buckle *et al.*, 1987).

The social system of rodent populations can have unexpected effects on attempts at management. In polygynous systems, it is generally assumed that the fecundity of the population is limited by the number of females, because each male can serve many females. Encouraging barn owls, *Tyto alba*, in oil palm plantations has been proposed as a means of controlling Malaysian field rats, but Lim *et al.* (1993) discovered that the owls selectively prey on male rats and thereby diminish their limiting impact on the prey. The bias probably arises because differences between the sexes of rat in ranging behaviour and habitat utilization make males more vulnerable to predation. In one plantation with a high population of owls, the sex ratio was found to be 60% female biased. Providing the population has a stable age distribution and there are no compensatory density-dependent effects, a 60% female sex ratio will increase the intrinsic rate of increase of the rat population by 20% compared with a 50% sex ratio. The consequences for the owl–rat interaction reduce the likelihood of an equilibrium at which owls limit the rat population, though the interaction of spatial density dependence with temporal dynamics may have a counterbalancing effect.

At the other extreme, a polygynous social system may eventually work to the advantage of pest management. Gosling and Baker (1989) suggest that when coypu females are rare and widely dispersed, a female sex ratio of at least 50% is required for population fecundity to be maintained. They show that the eradication of the coypu from East Anglia was enhanced by the greater trappability of the widely ranging males, a shortage of males being the most likely reason for the failure of increasing numbers of females to conceive towards the end of the campaign.

Foraging

Of all the components of rodent biology, their foraging behaviour – what, when, where, why and how much they eat – must be the most important from a practical point of view. Of course, rodents can cause all sorts of problems – brown rats transmit leptospirosis, beaver dams cause flooding, rat burrows cause subsidence in sewers – but the most common conflicts arise because they eat or spoil our food and gnaw at our buildings. Added to that, poison baiting is the principal method for combating pest rodents, and knowledge of the foraging behaviour and food preferences of the pest species is vital to the success of poisoning campaigns. Berdoy and Macdonald (1991) have reviewed aspects of foraging behaviour relevant to rat control.

The vast majority of work on rodent foraging behaviour has been carried out on the brown rat and the house mouse, and much of it under laboratory circumstances with domesticated strains. Laboratory studies have shown that rats can regulate nutrient intake and maintain a balanced diet in the face of deficiencies. They also exhibit innate preferences for some tastes and display true specific appetites, but their preferences are heavily influenced by experience, which may be vicarious.

Brown rats generally feed in bouts, and three or four bouts may result in more than half the total food intake each night. These bouts, though, are neither evenly nor randomly distributed, but tend to be most frequent at the beginning and end of the night. Berdoy and Macdonald (1991) found that a rat's feeding pattern reflected its social status: subordinate males compressed their feeding into the early daylight hours, presumably to avoid the dominants, which fed exclusively in darkness. Dubock (1984) suggested that the activities of dominant rats might make subordinates harder to poison, and used this as an argument for pulsed baiting, whereas Nott (1988) argued that subordinates might be less neophobic than dominants. Cox and Smith (1990) interpreted their field data as supporting Dubock's (1984) hypothesis.

Generally, brown rats are exceptionally wary of unfamiliar food. This so-called neophobia (neo = new, phobia = fear) has doubtless been enhanced by at least four centuries of concerted attempts by people to poison them. The result is that wild brown rats may avoid a pile of wheat in an unexpected place, and continue to treat it with great caution for more than a month. Moreover, when an individual rat has overcome its suspicion sufficiently to try this new food, it will only eat a small amount, perhaps 10% of its normal requirement. If it feels ill within the next 16 h or so, it will associate the illness with the ingestion of the novel food, and refuse to eat it again. This phenomenon, known as aversive conditioning or 'bait shyness', is commonly encountered when using acute poisons, such as zinc phosphide, which act within a few hours. One of the major reasons for the success of anticoagulants lies in the delay of several days between ingestion of the bait and the onset of symptoms, thus preventing the bait–toxicosis association and the development of bait shyness.

When the smell of a new food is on the lips of a rat, then its companions will more readily overcome their neophobia. This should assist in recruiting rats to a new food, as when 'prebaiting' a population with unpoisoned base bait before going on to use an acute toxicant in the bait. However, rats also learn from each other's misfortunes, and if a rat encounters a new food, and then meets a sick rat, the first rat will develop an aversion to the new food without ever eating it (Lavin *et al.*, 1980; Beck and Galef, 1989).

House mice are not neophobic, but they are sporadic and peripatetic feeders. This means that they will feed from 20 to 30 different sites each night, even favouring new food sources over old ones (Meehan, 1984); they might, therefore, be considered neophilic. The practical effect of this type of feeding behaviour is that mice will, like rats, tend to ingest only a small amount of poison bait from a new bait point, and will develop bait shyness if the toxicant has an acute action. For this reason, for both species, a large number of smaller bait points is desirable, not only to overcome group territorial boundaries, but also to increase the probability of individuals feeding from more than one point. There may be advantage in moving untouched or 'stale' points when baiting for mice, to make them appear new, but this would be counterproductive when baiting for rats, unless other evidence (e.g. absence of droppings, tracks) indicates that rats are not visiting the area at all.

Brown rats in some regions, for example Hampshire in England, seem to be exceptionally neophobic (Quy *et al.*, 1992; Brunton *et al.*, 1993). Brunton *et al.* (1993) found that on farms with these so-called behaviourally resistant rats, more than half of them may survive a control operation. This great caution is potentially an enormous problem for their control, but it must also cause the rats difficulties. Highly neophobic rats may forego many opportunities that their more adventurous ancestors could have grasped. Ironically, they prosper by restraining the opportunism that has been the key to their species' success. House mice also show behavioural resistance in at least one conurbation in the UK (Humphries *et al.*, 1992).

The Ecological Ethic

The purpose of this chapter has been to introduce something of the diversity of rodents and to show that in managing the tiny minority of species that are significant pests it is important to understand their ecology and behaviour. Rodent pests have a huge economic impact and, therefore, increasing effort and resources are being directed towards studying their natural behaviour with a view to utilizing that to develop management strategies. In most species, there remains a paucity of data concerning the epidemiology of disease. For instance, an exploratory investigation into the parasites of wild brown rats on UK farms found unexpectedly low prevalence rates of *Leptospira icterohaemorrhagiae*, a serovar of leptospirosis that is especially dangerous to humans (Webster *et al.*, 1995). Nonetheless, the incidence of leptospirosis in rats from Danish sewers has proven to be significantly higher, with prevalence rates reaching 89%, suggesting that there are high levels of environmental transmission (Krojgaard *et al.*, 2009). Leptospirosis is an important emerging infectious disease (Faine, 1998), so identifying factors that influence its transmission between rats, other rodent and domestic reservoir hosts and people is vital.

As the concept of restoration ecology permeates conservation, so species are being reintroduced into their historical areas. On several islands worldwide, the loss of endemic fauna and flora has been attributed in part to the presence of commensal invasive rodents on the islands, with *Rattus* perhaps being the most widely introduced of all vertebrates (see Chapter 18). On the Great Barrier Island in New Zealand, trapping of rodents alone was found to be insufficient to enable avian reintroductions, whereas a combination of trapping and strategically pulsed toxin baits did achieve low levels of rats (Ogden and Gilbert, 2009).

The regrettable fact that there is often no cost-effective alternative to poisons in rodent control raises many fears about non-target victims, secondary poisoning and the general hazards of dealing with highly toxic materials (see Chapter 16). The use of 'second-generation' rodenticides has become widespread throughout agricultural practice, raising concerns over secondary exposure and the poisoning of non-target predators. The polecat, *Mustela putorius*, preys on farmyard rats in winter in Britain and is thus highly vulnerable to secondary rodenticide poisoning. Some 26% of animals in one study were found to contain difenacoum or bromadiolone, with the exposure being both geographically and temporally widespread (Shore *et al.*, 1999). A general principle of wildlife management is that intervention should be kept to the minimum necessary to achieve a specific desired result with the minimum of undesirable side effects.

An ecological ethic could fruitfully be brought to bear on the problem of behaviourally resistant brown rats, as discussed by Brunton *et al.* (1993). Anticoagulant poisons have provided an environmentally relatively safe solution to rat control. Where warfarin resistance thwarted control, second-generation anticoagulants such as difenacoum provided an alternative. However, there are increasing reports of rodents becoming resistant to the second-generation rodenticides, and there is an increasing demand for low-residue control chemicals for use on islands where repeated application of brodifacoum or similar rodenticides is likely to result in contamination of wildlife or game species, and secondary poisoning of non-target species (Eason *et al.*, 2010).

This situation leads to increasing demand worldwide for rodent-control strategies that rely less on chemical rodenticides, or adopt a more focused approach to their use, in conjunction with ecologically based pest management (EBPM). There are several advantages in viewing rodent pest control as an integrated ecologically based approach rather than a single drive for control, as reviewed by Singleton and Brown (1999) (see also Baker *et al.*, 2007; Chapter 33).

Rodents are the largest, and probably the most successful, mammalian group, facets of which have integrated themselves into almost every niche on land, in some places becoming a serious pest issue. In order to combat this, and to maintain pace in the arms race, it will prove necessary to continue in the quest to understand both the intrinsic and extrinsic factors that affect different rodent species, and through which the control of pests might be managed.

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2 Commensal Rodents

M. Lund
Formerly of Danish Pest Infestation Laboratory,
Institute of Integrated Pest Management, Slagelse, Denmark

Introduction and Economic Importance

The damage caused by field rodents may sometimes be estimated roughly for local districts where a measurable proportion of various crops is destroyed by the rodents (see Singleton *et al.*, 1999). Commensal rodent damage is more difficult to assess, primarily because so many different items can be involved and rats and mice can invade almost any type of structure. In certain parts of the world, damage may begin with the crop in the field, as with the house mouse in Australia's wheat-growing areas and the roof rat on sugarcane, rice, wheat, coconuts, cocoa and other tropical crops (Table 2.1). In industrially developed countries with an overproduction of most crops and adequate storage facilities, commensal rodents are controlled primarily for hygienic and public health reasons, and only secondarily because of the damage inflicted on stored crops or other food and materials. The opposite is true for most countries in subtropical or tropical regions. Here, food shortage is often a recurring threat to human populations and the damage caused by commensal rodents to stored crops – or in certain situations to field crops – can make the difference between life and death (Table 2.2). Furthermore, rodent hair or droppings in food may create great problems for exporting countries so that entire loads are rejected by the authorities in the importing country. In food stores and warehouses, rats and mice can cause great problems, not only by consuming or fouling a substantial part of the food, but also because they destroy sacks, bags, boxes and other packaging materials (see Chapter 11).

In developing countries, commensal rodents may attack crops shortly after they have been planted or sown, but they are usually most vulnerable close to harvest (see Chapter 10). As storage facilities at the village level are always very primitive, e.g. lofts of dwelling houses or clay storage huts, there is easy access for rats and mice. Often, fairly small changes or improvements in such storage facilities would reduce rodent damage considerably (see for example Sarangi *et al.*, 2009), but such improvements are rarely implemented and maintained. Though few figures are available (Meehan, 1984), almost any crop can be damaged, but the most important are maize, rice, sorghum, millet and wheat. Locally, oilseeds, groundnuts, cotton seeds, sunflower seeds, linseed and coconuts are also highly vulnerable. Rats may also be very harmful to sweet potatoes, yams and other root crops.

In industrial countries, rats eating animal feed on livestock farms are generally not considered a serious problem, but extensive damage may occur if they gnaw electric

Table 2.1. Estimated losses of food crops due to damage by commensal rodents (various sources).

Field crop	Area	Estimated damage or loss (%)
Cacao	Solomon Islands	1–9
Carobs	Cyprus	3
Coconuts	Fiji	5–13
	Ivory Coast	10–15
	Jamaica	5–36
	Philippines	57
	Tahiti	27–47
	Tarawa	23
	Tokelau Islands	30–40
Macadamia nuts	Hawaii, USA	16
Rice	Bangladesh (deepwater rice)[a]	6
	India	6–9
	Java, Indonesia	40
	Philippines (national survey)	2–18
	Philippines (outbreak year)	90
	Philippines (yearly average)	10
Sugarcane	Barbados	6
	Hawaii, USA	4–40
	Jamaica	5
Wheat	Bangladesh[a]	12
	Pakistan[a]	3.5

[a]Includes damage by *Bandicota* spp.

Table 2.2. Estimated damage and losses of stored crops and other foodstuffs due to commensal rodents in tropical and subtropical areas (Hopf *et al.*, 1976).

Area	Type of storage	Commodities attacked	Damage or loss (%)
Brazil	Stacks, sacks, cribs	Rice, maize, beans	4–8
Bangladesh	–	Rice, pulses, grains	2–5
Egypt	Open and closed stores	Cereal grains	0.5–1
Ghana	–	Maize, rice, grain	2–3
India	Warehouses, sacks	Cereal grains	5–15
Korea Republic	Sacks in houses and stores	Rice, barley	20
Laos	Stores	Rice, maize	5–10
Malawi	–	Maize, rice	1–7
Mexico	Granaries, sacks, cribs	Maize, rice, groundnuts	5–10
Malaysia (Sarawak)	Cribs	Rice	5–10
Nepal	Sacks	Maize	3–5
New Hebrides (Vanuatu)	Covered platforms	Yams	10
Nigeria (Kano State)	Temporary or closed stores	Pulses, groundnuts	3–5
Philippines	Warehouses, sacks	Rice, maize, legumes	2–5
Sierra Leone	Temporary cribs or sacks	Rice, maize, groundnuts	2–3
Solomon Islands	–	Yams	5
Thailand	Sacks, cribs	Maize, rice, copra	5
Turkey	Warehouses, sacks	Wheat, rice, maize, legumes	5–15
Tunisia	Warehouses	Cereal grains, legumes	6–8

cables and cause fire (see Chapter 11). As the farms in which this happens often burn down completely, it can be hard to find the cause of the fire afterwards. This may also happen in ordinary dwelling houses, but usually the risk is reduced as any cables are not close to stacks of straw or hay.

A particular problem in industrialized countries is the high number of brown rats in the sewer systems of cities. This is often the last place they can find shelter in modern situations where slums are no longer present and where garbage removal works so well that the rats have problems in finding something edible above ground. In many countries, rat control is either not carried out in sewers, or if it is, then it is done in a less systematic way than on farmsteads. This may lead to a very high density of rats in sewers and, consequently, a surplus seeking shelter elsewhere. It is generally agreed that rats in sewers are not a problem by themselves, as they do not damage properly installed and intact pipes. They usually only appear where leakages already exist, but it is always serious for the owner of a dwelling house if rats appear under a concrete floor. A broken pipe or unplugged drain has to be found and repaired as otherwise waste water may be spilled out of the system for long periods.

As all materials not as hard as the enamel (5.5 on Mohs hardness scale) on the rodent's incisors can be gnawed, damage may be inflicted to a wide variety of items within the walls of a structure. Most damage is, however, found on softer materials, such as those made of plaster or wood, and including electric wires, door frames, window sills, floors and textiles.

In the slum areas of large towns, rats may gnaw elderly and helpless people during the night or babies when they are not being looked after. This is extremely rare in north-western Europe and always produces headlines in the newspapers, but in certain villages in developing countries there is a constant fight between humans and rats when hungry rats try to gnaw the fingers and toes of those trying to rest.

In the USA, and especially in countries in South-east Asia, the bite of a rat may give rise to diseases caused by two different bacteria: *Spirillum minus* and *Streptobacillus moniliformis*. Rats are further feared because they may transmit murine typhus, leptospirosis (especially Weil's disease) and even plague, which is still a disease of concern in the Americas, Africa and South Asia. The house mouse is primarily a health problem via its transmission of *Salmonella* bacteria to various types of prepared food or to livestock, by which means it creates infectious food poisoning (see Chapter 4).

Where rats are controlled systematically, whether directly by rodenticides or indirectly through preventive measures, house mice may become a problem instead. This has been seen in London (Rowe, 1987), where mice can inflict serious damage in bulk food stores, food-processing plants, mills, bakeries, shops and restaurants. In rural areas, granaries, silos and animal feed stores, as well as piggeries and poultry houses, are the preferred habitats for mice. A mouse only consumes 3–4 g of cereal a day, in contrast to 20–30 g by a rat, but mice waste much more food through their erratic way of feeding and by only eating part of any grain. A mouse may void 50 droppings a day and these can be very difficult to remove, especially from grain. All concerned with rodent control know that the cost of damage by commensal rodents in developing countries can be devastating. In industrialized countries, commensal rodents must be controlled to prevent population densities reaching levels at which rats and mice become a risk to humans, or the cost of the damage inflicted increases to an unbearable size. No recent estimate of overall damage by commensal rodents exists – the best information available goes back to 1976 (Hopf *et al.*, 1976) (Tables 2.1 and 2.2), although there are more recent estimates from various countries.

In a recent survey in Pakistan (Brooks *et al.*, 1990), it was reported that in 1 year rats inflicted 2–9% damage on irrigated wheat fields preharvest, and 3–8% damage on rice fields. Sugarcane and groundnuts had 'considerable' damage. In stores, losses were estimated to be around 1% in government-owned structures, but up to five to ten times higher at the farm and village level.

In Australia in 1969–1970, one of the recurrent plagues of house mice destroyed almost 200,000 t of wheat, oats, maize and sorghum. In one of the main irrigation areas, the average damage to all standing crops in the same year was estimated to be more than 15%. In the state of Victoria, a survey in 1979–1980 gave even bigger losses, and in 1984 a mouse plague in South Australia, Victoria and New South Wales was reported to cause the same level of damage as the earlier outbreak in 1969–1970 (Saunders, 1986).

Greaves (1988) estimated that around 94% of the farms in Hampshire (England) were rat infested in 1979–1980; this was one of the worst damaged areas in the country, with damage in other areas varying from 21 to 44%. Losses from damage to stored grain and animal feed were estimated to be worth £10–20 million a year.

Bajomi and Sasvari (1986) claimed that there were an estimated 2 million rats in Budapest in Hungary in the years 1978–1985, and that they caused damage worth US$6.4–8.5 million annually. A survey revealed that around 30% of apartment buildings were rat infested, with infestation of family houses at 17.2%, non-food-manufacturing plants at 15.2%, food-manufacturing plants at 13.3% and public institutions at 13.1%.

A very accurate estimate of food loss in warehouses in Cuba was made by Hernandez and Drummond (1984), who found that the cost–benefit ratio of controlling commensal rodents in the warehouses was very favourable (see Chapter 10).

Cosmopolitan Pests

The brown, common or Norway rat (*Rattus norvegicus*)

The brown rat (see Fig. 2.1) is a fairly recent companion of man. Up to around 1700, this species is believed to have led an obscure life in the deserted, grass-covered steppe areas north of the Caspian Sea in what was, until recently, the USSR. The reasons for its sudden emigration from this region are not clear – earthquakes, or just a series of favourable breeding seasons creating a higher population density and a consequent pressure for migration, have been suggested. The species spread to more densely populated areas of western Russia in the first decade of the 18th century and may not have met its optimal habitat until then. In stables and barns on Russian farms, the brown rat found a rich supply of food and it responded with what can only be called an explosion in numbers.

Fig. 2.1. The brown rat, *Rattus norvegicus*. A reproductive brown rat is 19–25 cm long (head + body) and the tail is 16–20 cm long, usually darker on the upper side than below.

From Russia, it migrated further, or was transported by ship, to almost all other parts of the world. The famous German/Russian naturalist Pallas claimed that he knew the exact day on which brown rats invaded Europe from Russia. He referred to eyewitnesses seeing, on a certain day in 1727, huge numbers of brown rats swim over the Volga River close to the town of Astrachan. Whether this statement is true or not, it is a fact that this rat invaded many European countries in the first half of the 18th century.

Denmark is mentioned as one of the first places reached by the brown rat; it was a passenger aboard the ships carrying Czar Peter and 35,000 men on a visit to Copenhagen in 1716. Rats reached England (London) by ship in 1731, whereas Paris was not invaded until 1753, although they had become a serious pest in both cities by the end of the century. Germany was entirely colonized by rats in the middle of the 18th century, and they reached the USA on board English vessels a few years after they had arrived in London. The brown rat seems to have established itself on the east coast of the USA around 1740, and from there it spread all over the country, a process which is still continuing in Canada. The species was originally conditioned to live in temperate regions, but as a commensal pest with great adaptive capacities, it has succeeded in working its way deep into the continental tropics, starting at the coast and moving along rivers from settlement to settlement.

This process is still going on in subtropical as well as tropical regions in Africa, Asia and South America (Fig. 2.2).

In most areas where the brown rat has appeared, the presence of the other widespread rat species, the roof rat (*R. rattus*), seems to be under threat. This may be due to direct competition, as the brown rat is a more aggressive and strong type of animal, but other factors may be involved, such as the historical change in the construction of buildings from half-timbered to brick built. The negative influence of the brown rat on the roof rat seems not to occur in California and some other states in the USA, or in Myanmar, where the larger sized lesser bandicoot rat (*Bandicota bengalensis*) is taking over many of the previous out-of-door sites previously occupied by the brown rat. As a true commensal species, the brown rat usually thrives only near human settlements, or where humans supply extra food as at garbage dumps or at feeding places for game inside forests. On uninhabited islands, rats may become a threat to ground-breeding birds, but usually their numbers change seasonally depending on the food available.

Whenever food, water and shelter are present there is always a basis for the establishment of rat populations. This situation is found in villages and farms all over the world, and especially in developing countries, where the garbage removal system in many larger cities does not work adequately, and where slum quarters are present. Experience in the Western world in the 1960s and 1970s has shown that an improvement of the garbage removal system can reduce rat numbers drastically without any increase in rodenticide use. In Western cities, the rat is primarily found in the sewer systems, where the temperature is relatively uniform throughout the year and where food is usually available. Rats in sewers are not a great problem, as long as the systems are intact, but this is never the case. Sewer-inhabiting rats do not breed in the pipes carrying sewage liquid; they either build their nests in dry side branches of the system, or if these are not available, try to find small openings and place the nest outside the system in the soil. If there is a leakage beneath a house, rats may come out and establish themselves under the floor and spoil, among other things, the insulating material. Stray rats from sewers may

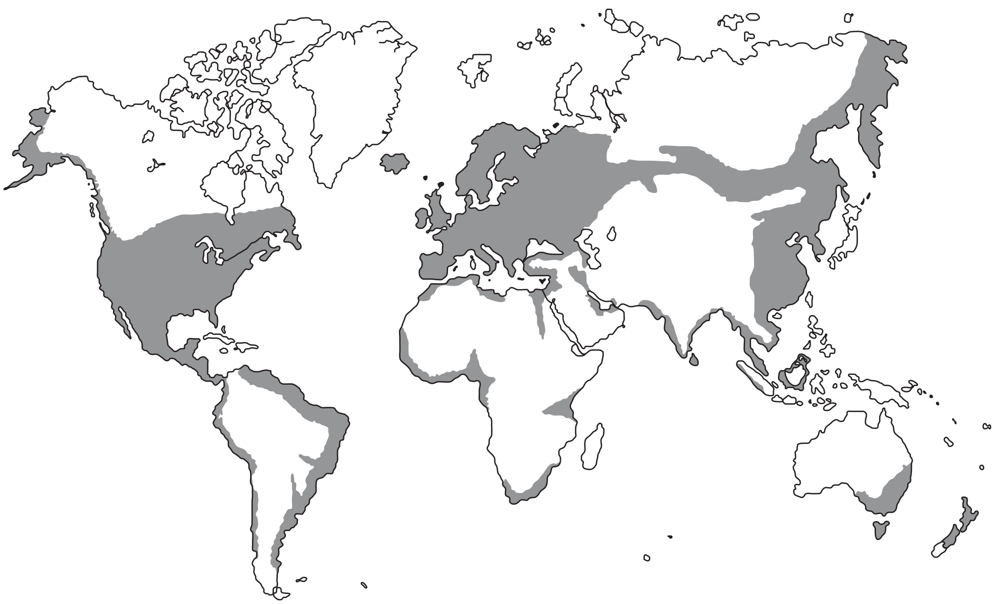

Fig. 2.2. Distribution of the brown rat, *Rattus norvegicus*. (Modified after Brooks, J.E. and Rowe, F.P., 1987).

also invade parks, recreation areas and gardens, from where they may find their way into houses. In rural areas, life is easier for the rats, most stables and barns are easily entered, and food and shelter are readily available. In such places continuous rat control is the only solution to the problem.

Although the brown rat is not as agile as the roof rat, it climbs brick walls fairly well, especially if it can press against a vertical object like a downpipe. It is well known that rats can climb inside waste pipes up to the fifth floor. Only a few sewer rats do this when population density is very high, and only a small fraction of these climbers are able to find their way through the water seal of the toilet and appear on the toilet seat, though these rare occurrences are widely reported! It has been shown by video cameras and transparent pipes how the rats climb; they simply press their forelegs and hind legs laterally against the sides of the pipe, without using the tail or the back. The width of the pipe generally is around 100 mm, or a little less than an adult rat can reach with its legs. As a young rat only needs an opening of about 25 mm in diameter to squeeze through, it is very difficult to prevent rats from entering houses where the roof meets the walls.

The social behaviour of the rats – their tendency to live in colonies (Chapter 1) – can to a certain degree be explained by the availability and the amount of food present. Cattle or pig feed is commonly concentrated in small areas, and if rat shelters are in the walls or loft, they are forced to be social. They must settle close to other family groups, but they still defend a territory around their own group. If food is more scattered, as at fish breeding ponds or on uninhabited islands, the rats are found in a more dispersed manner than they occur on farms and in sewers.

The reason for the obvious success of the brown rat is its adaptability or lack of specificity. It is omnivorous and can eat almost any biological matter. This does not mean that it is an indiscriminate feeder. It can be extremely fastidious, if it has the opportunity, and this is the reason for the great amount of effort put into the management of palatable baits for rats. A poison bait always has to compete with existing non-poisonous food. An 'average' rat usually prefers a high-quality cereal to anything else, but local conditions in the rat population may moderate such a preference. Studies by Galef *et al.* (1988) indicate that a rat can learn from its companions to prefer a certain type of food. The cues seem to be a combination of the odour of food items with that of tiny quantities of carbon disulfide (CS_2) that are found in the breath of rats and mice. Studies to establish whether these findings can be used to attract rats to baits or bait boxes smelling of CS_2 are, however, still inconclusive (Mason *et al.*, 1988; Lund and Lodal, 1990).

The adaptability of the rat, as far as food preferences are concerned, is seen well in sewer rats, which can thrive on the variety of waste food in drains. To a certain extent, they can live on human faeces, but they always prefer waste from restaurants and food-processing industries. Especially in the USA, waste from apartment blocks contains a lot of edible materials from the grinders that are found in most kitchen sinks.

Rats on small islands may gorge on eggs, chicks and adult birds in the breeding season, but at other times they may come close to starvation. The rat may prey on many small vertebrates, including the house mouse, but where cereals are abundant, the two species can coexist as in farm buildings and warehouses.

An adult rat consumes 20–30 g of a grain a day; this means that 100 rats on a farm will take at least 1 t of the feed meant for livestock during a year. This, and the potential risk of transmitting various diseases to man or livestock, are the main reasons for the intensive rat control measures carried out in many countries.

In spite of the rat being a burrowing steppe animal, out of doors it prefers to stay close to streams or ponds. It is a very capable swimmer and diver and is able to take ducklings in the water or capture trout in fish ponds; this is also the reason why it thrives well in sewers, where the roof rat does not establish itself.

The group territory of rats, often associated with one male and one to several females with their offspring, is usually rather small, with a diameter of 10–30 m. Quite often, rats live in, for example, a barn filled with straw, and feed in structures next to the barn; here, territories are difficult to define. Rats frequently have small territories around the nest site but feed in common on neutral ground, such as a storage room for feed or grain; here, they do not show much aggressive behaviour towards each other. Radio-tracking studies show that brown rats may cover considerable distances to feed – from hedges to a farm building, or when they feed on crustaceans and fish at low tide in tidal areas. In such situations, a rat may travel 1 km or more a night.

The size and weight of an average mature brown rat is difficult to give, as animals may become reproductive at an age of 2.5–3 months when their weight can vary from 100 g to 150 g. At the height of their lives, when they are around 8–10 months old, their weights may range from 300 g to 400 g. Only the rare individual reaches higher weights than that in ordinary populations, though local populations are found with extreme weights. In Iraq, along the Tigris River in Baghdad, unusually large individuals weighing up to 770 g (personal observation) are found very commonly, and in a couple of US cities the same seems to be true.

The roof, ship, house or black rat (*Rattus rattus*)

This rat (see Figs 2.3 and 2.4) is the original rat of temperate as well as subtropical and tropical zones. Until the beginning of the 18th century, it was the only rat species found more or less worldwide. Its history is largely unknown up to the time of the Crusades, but skull fragments found recently show that it was present in Western Europe (England and France) as early as Roman times (AD 100). It is generally accepted that the species had an arboreal origin in forested areas of equatorial South-east Asia. Its climbing capabilities are much better than those of its relative the brown rat, which originated in treeless areas. The roof rat apparently spread all over the Old World shortly after the start of the Christian era (Vigne and Femolant, 1991), and did not meet its major competitor, the brown rat, until the latter spread from central Asia at the beginning of the 18th century. The roof rat arrived in the New World at the time of Columbus, and South America is still, apart from Australia, the only continent where this species is primarily confined to the coastal areas. In South and South-east Asia, and Africa south of the Sahara, the species is almost universal and not seriously threatened by the brown rat, which is still expanding its range in the tropics. Although the roof rat was common in northern and western parts of Europe up to the 1960s, where it was mostly confined to the larger cities and port areas, it has today become so scarce that it has become a protected animal in Sweden and Germany. That it is still an extremely important pest animal in the subtropics and tropics does not seem to embarrass those responsible for its protection.

Fig. 2.3. The roof rat, *Rattus rattus*. A reproductive roof rat measures 17–20 cm (head + body) and the tail is 20–25 cm long.

On the east coast of South America, the roof rat follows some of the larger streams deep into the continent, as along the Paraná and Uruguay rivers and in southern Brazil. On the Pacific coast, its distribution is limited to a narrow strip along the coast of Peru and Chile. It has spread through the whole of Central America to California, where it is at present a very serious pest, and through New Mexico and Texas to Florida, West Virginia and Maryland. In western Asia, Israel, Lebanon, Iraq and Syria, the roof rat loses ground to the larger brown rat, and in Iraq and Turkey, it is mainly found in coastal areas. In Asia, it is abundant along the foothills of the Himalayas and southwards and eastwards

Fig. 2.4. Distribution of the roof rat, *Rattus rattus*. (Modified after Brooks, J.E. and Rowe, F.P., 1987).

through south-east China, Japan and the Philippines, Indonesia, New Zealand and the coasts, especially those of south-east Australia. It spread rather late to the Pacific islands, mainly during World War II. On some islands, it is already replacing the Polynesian rat (*Rattus exulans*) as the most abundant species, and it may be found far from human settlements in dense rainforests as well as in mangrove swamps. At other sites, it is a true commensal, living inside houses and storage facilities, or in many crops (e.g. coconut, sugarcane).

Roof rats usually prefer the upper parts of dwellings, whereas brown rats often keep to the lower parts, or burrows in the ground outside the house. At one time, the roof rat was divided into several subspecies on account of its great variation in coat colour – from dark grey or black, a type which is mainly found in Central Europe, to brown with a yellowish or grey belly. As all different colours can be found in one litter, colour alone cannot be used for discriminating between subspecies.

The roof rat is less omnivorous than the brown rat (Yabe, 1979), and animal food is less significant to it. Japanese studies have described the food preferences of the roof and brown rat species in Japan, where both are common. The percentage of animal materials in the stomach of the brown rat was always higher (26–28% in volume) than that of the roof rat (5–11%) in different habitats. The roof rat preferred fruits, seeds and grain (51–59%). Only in a livestock experiment station did assorted feed become the main diet of both species. When the roof rat cannot find seeds or grain, it disappears.

In contrast to the feeding patterns described above, roof rat populations may develop distinct feeding traditions, not only as far as dietary preferences are concerned, but also in the motor patterns employed in food acquisition (Aisner and Terkel, 1991). In Israel, populations exploiting the seeds from cones of the Jerusalem pine (*Pinus halepensis*) and other seeds from cones, such as those of the cypress (*Cupressus sempervirens*), have been described. Small populations, settled in the centre of such plantations, use the cones as their only food and stay in the trees almost permanently. Studies have shown that the skill of the mother in handling the cones is passed to the offspring through a process of cultural transmission; rats from other populations are not able to open the cones.

The roof rat, with its preference for cereals and fruits, is not as common on livestock farms as the brown rat. Instead, it is more common in food stores, markets, grain elevators, ordinary houses, flats and shops in the warmer parts of the world. In spite of occupying drier habitats than the brown rat, the renal efficiency is almost the same in the two species (Yabe, 1983).

The roof rat is more agile than the brown rat and may run from structure to structure on telephone wires, and can easily climb the walls of buildings. Inside buildings, it most often prefers to nest high up under the roof, but in subtropical areas it frequently nests in trees, e.g. palms, and in some wooded areas in Spain, southern France, Israel and other Mediterranean countries, it effectively fills the niche of a squirrel.

In many regions, the roof rat is a serious pest of orchards and plantations, damaging all sorts of fruits and nuts. In Africa, in contrast, it keeps to huts and houses and rarely moves far out into the fields. It is more widespread in South-east Asia, where it is considered equally common outdoors and indoors. Its decline in most countries of northern and western Europe, and in certain parts of the Middle East, such as Iraq and Israel, can be correlated with the increased distribution of the brown rat in the same areas. The spread of the roof rat also seems to have decreased because of the changed construction of modern ships and the use of containers; the fewer boats plying their trade in northern Europe have also played a role in the decline of the roof rat in this part of the world. The species is not, however, losing ground everywhere, and its importance in southern California, where the brown rat is also common, makes it difficult to work out the exact relationship between the two species. In direct confrontations, the roof rat is less aggressive than the larger brown rat, and usually gives way without direct fights, moving to areas that are not easily accessible to the other species.

The house mouse (*Mus* spp.)

The house mouse (see Figs 2.5 and 2.6), or better, house mice, as several species represent what was previously considered to be one (Auffray *et al.*, 1990), live independently of man in certain areas of the world, although in others they are strictly commensal. Discussions are still going on about how many species of house mice live in Europe (Marshall and Sage, 1981). The evidence that in north-west Europe the house mouse belongs to two species, *Mus musculus* and *M. domesticus*, comes from the existence of a narrow (20 km) and stable hybrid zone, with little introgression into neighbouring populations, in Jutland, Denmark, and southwards through Germany, and the finding that the hybrids seem to be less reproductively successful than those outside the zone.

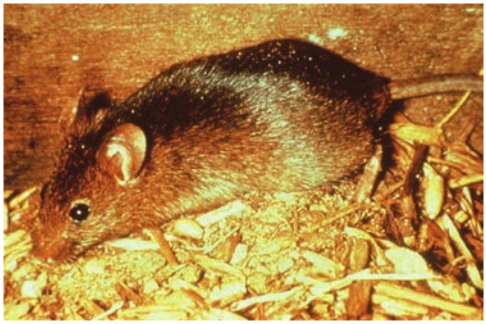

Fig. 2.5. A species of house mouse, *Mus domesticus*. The total length of adult house mice is around 18 cm. In *M. domesticus*, the tail is somewhat longer than the head + body, while in *M. musculus* it is a little shorter.

According to Marshall and Sage (1981) the following species of house mice are found in Europe and Asia:

1. *M. musculus*, or Linnaeus' house mouse, has a more convex skull seen from a lateral view than the other species. The incisors in the upper jaw are not as curved as in the other species, but they have the same distinct notch close to the distal end. The colour of the fur is greyish brown on the back and whitish on the belly, with a fairly sharp demarcation line. This was the type that Linnaeus originally (1776) described in Uppsala, Sweden. Apart from its presence in Sweden, this species is found in eastern Denmark and east of a line going southwards through Germany and ending up in Serbia, in the Balkans. In northern and

Fig. 2.6. A rough indication of the distribution of the various species of house mice, *Mus* spp., indicated by the relevant capitalized specific (or subspecific) epithet.

central Asia, a very closely related house mouse is found that prefers desert areas and has long soft fur, even on the tail (*M. m. wagneri*).

2. *M. domesticus*, or the European house mouse, is found both in Europe and in other countries. Its distribution in Europe meets that of *M. musculus* in the western part of Denmark and through central Europe; it is the only species found in England and the Netherlands, and it also occurs in Belgium, France and Spain. It is slightly larger than *M. musculus*, usually uniformly greyish or brownish all over, and with a tail that is at least as long as the head plus body. *M. domesticus* may adapt to local settings by colour variants: in northern Africa, for instance, there is a mosaic of dark- and white-bellied forms, and it is polymorphic in Egypt, Syria and Israel. Further eastwards, more sandy brown animals occur (in Arabia and Pakistan). The species is generally more confined to buildings than *M. musculus*, but in the absence of competition from other small animals, it is also found in agricultural fields and in vegetation changed by man. It is this form which has been taken by man to the Americas and Australia.

3. *M. spretus*, or Lataste's mouse, is found at the western ridge of the Mediterranean Sea in southern France and Spain, where it lives sympatrically with *M. domesticus*. It is the only species of house mouse that has no notch in the upper incisors. Its tail is fairly short, and it has distinct differences in fur colour from back to belly.

4. *M. macedonicus* (*M. abbotti* or *M. spretoides*), the Eastern Mediterranean short-tailed mouse, is found in natural vegetation and fields from Macedonia through Turkey and north-west Iran to the southern rim of the Caspian Sea. This species also lives sympatrically with *M. domesticus*.

5. *M. hortulanus* (*M. specilegus*), the mound-builder, hillock or steppe mouse, is found in the wheat belts of Ukraine, Romania and Austria in the same area as *M. musculus*, but the latter usually lives in farm buildings, whereas *M. hortulanus* prefers granaries or grain fields. *M. hortulanus* can be considered an important member of the steppe fauna in eastern Europe, and may have migrated to Europe from Asia around the Black Sea.

6. *M. molossinus* is the wild mouse of Japan, and seems to be closely related to

M. musculus. It lives both inside and outside buildings.

7. *M. castaneus* (or *M. musculus castaneus*) is the Asian house mouse. It is very closely related to the presence of humans in its occurrence and probably has no feral range. The species is limited to cities and towns from India to the islands in the Pacific region (Japan, Taiwan, the Philippines), but it is reported to be rare in Thailand, where *Rattus exulans* is the prevailing 'house mouse'. It resembles *M. domesticus* of Europe in many ways, but is much smaller.

The house mouse is known to have lived in Israel 12,000 years ago, and was probably present in the first agricultural settlements in Mesopotamia and Egypt, originating in areas around or in Pakistan. In the Mediterranean area, the spread seems to have been very slow up to around 2000 BC, at which time it began to establish itself in southern Europe. The house mouse is still extending its range in remote areas such as Guadalcanal Island of the Solomon Islands, and on other islands close to the Antarctic region. Depending on climatic conditions and primarily on the presence of mammalian competitors or predators, it has established itself out of doors on such islands as Skokholm (UK), the Faroes in the North Atlantic, and Gough Island in the South Atlantic. In most of Europe, the house mouse has not been successful in the field, as it seems not to compete well with indigenous rodents such as *Apodemus* and *Microtus* spp. The same is true for large parts of North America, where *Peromyscus* spp. especially compete with the house mouse. In South America and parts of Africa, local species also prevent the house mouse from becoming a serious pest on crops. In the wheat belts of South and South-east Australia, where the climate is suitable, and where local species do not present serious competition or predation, in certain years the house mouse reaches incredible numbers in the field and consequently also inside buildings (Singleton and Redhead, 1990).

The house mouse is an extremely adaptable animal. In temperate regions, it usually breeds seasonally, but inside structures and even in complete darkness in deep coal mines, it may breed continuously through the year. In contrast to the rat species, which cannot survive more than a few days without access to water, the house mouse reacts almost like a desert animal and can survive without drinking by exploiting the water created by metabolism and by considerably concentrating the urine. In certain dry environments, where the food contains a minimum of water, there may be a decrease in reproduction; this increases again if the mice obtain access to only a little morning dew (Newsome *et al.*, 1976). The house mouse may thus be found in deserts in South America and Australia, on arid islands, on beaches and in salt marshes.

Female mice, in particular, require a very high calorific intake for growth, for keeping warm and for reproduction. The amount of body heat that is lost because of the high ratio of body surface to body weight is extreme – this is the reason why the narcotic rodenticide, chloralose, works much more efficiently on house mice than on larger rat species. However, if the environmental temperature is higher than 16°C, chloralose cannot be used successfully, as a large proportion of the mice recover from the induced coma.

It must be also mentioned that house mice have been of great benefit to man in the form of the laboratory mouse. The domesticated house mouse, which is the most widely used experimental animal, has made important contributions in many fields of research, not the least in the biomedical sciences. The house mouse has been domesticated for several thousand years and used scientifically at least since 1664. Modern strains were developed from pet mice, and to some degree also from wild mice, after around 1908 (Berry, 1984).

A good general account of the biology of the three common commensal pest rodent species, *R. norvegicus*, *R. rattus* and *M. domesticus*, within a European context, is provided by Harris and Yalden (2008).

Locally Important Commensal Rodent Species

In certain parts of the world, indigenous rodent species may be more important to humans than the three introduced species (brown and roof rats and the house mouse) discussed above. These local species may have a close tie to the local environment, and may be less dependent on the presence of humans. When food is scarce in the fields, they may move close to or inside buildings and thereby damage foodstuffs and materials and become a threat to human health, like the three major species. A few of the more important of these 'semi-domestic' species are described here.

The multimammate rat (*Mastomys* (*Praomys*) *natalensis*)

In most parts of Africa south of the Sahara, this small rat (head + body 100–150 mm; tail approximately the same; weight 35–110 g) is extremely common in most years and, in many countries, seriously damages crops. It reaches peak numbers in the dry season after harvest, and then invades villages and storage huts, attacking almost any food or solid material. This semi-commensal biology makes the multimammate rat particularly important as a transmitter of plague from field rodent populations to the roof rat inside built structures.

This is primarily a granivorous species, but with a certain percentage of insects in the diet, although in contact with man it often becomes completely omnivorous. The species is not a very aggressive animal and may live at very high densities without any overt fighting. It usually lives in underground burrows, which it rarely digs out itself but takes over from other rodent species. Inside structures, it prefers, like other commensal rodents, to nest in dark places. The multimammate rat is considered to be one of the most prolific of all mammal species; it has up to 23 young in one litter (average litter size around 12), and breeds at intervals no longer than 25 days. It usually stops breeding in the dry season and starts again at the first rains, when the fields are cultivated. A study in Tanzania (Telford, 1989) showed that the maximum density of the species was 1125 ha^{-1} in October, and that it produced three to four litters from April to August. Seasonal breeding may occur in fallow maize fields after short rains in January–February.

The lesser bandicoot rat (*Bandicota bengalensis*)

The lesser bandicoot rat looks very much like an adult brown rat, except that the guard hairs on the back are more prominent. However, the average size of the animal varies considerably from region to region in South and South-east Asia (Aplin *et al.*, 2003).

The bandicoot rat also resembles the brown rat in many other biological aspects, primarily by being a burrowing rodent and having a preference for moist or wet habitats, and by being an excellent swimmer and diver. Since the turn of the century, it has gradually become a commensal rodent in urban areas of South Asia, and in many places has actually replaced the brown rat and, at certain sites, also the roof rat; it is now a major commensal pest in Mumbai, Chennai, Kolcatta, Rangoon, Bangkok and many other large cities in South and South-east Asia. By its burrowing activities, the bandicoot rat often blocks storm gutters and drains, and it may also cause the collapse of building foundations, or damage streets and pavements. Even if it does not settle indoors as readily as the two *Rattus* spp., it has become a serious pest in grain stores, food shops, bazaars, restaurants and private homes. It usually has its nest outside buildings, and does not like to climb.

The reproductive biology of the species is similar to that of the brown rat. The number of embryos varies from one to 14, but the average number of young per female was found to be 7.4 in one study in Rangoon (Walton *et al.*, 1978). In another study, 5.9 pregnancies per female were registered, or 43 young per female. The success of breeding is significantly reduced by the monsoon rains. The social behaviour of the bandicoot rat has been studied by direct observations in godowns (warehouses/stores) in Kolcatta (Franz, 1976), and it seems that its social structure is looser than in the two *Rattus* spp., in that it is highly tolerant towards conspecifics. Its movement in grain stores is fairly limited, and is rarely over a distance more than 60 m and only occasionally up to 170 m.

The Polynesian rat or Burmese house rat (*Rattus exulans*)

The Polynesian rat has an extensive distribution in South and South-east Asia. It is found roughly between the Tropics of Cancer and Capricorn, although its distribution also extends to islands around New Zealand to the south (Aplin *et al.*, 2003). Its north-western limit is eastern Bangladesh and its western limit the Andaman Islands, Mentawai Islands and Christmas Island in the Indian Ocean. In Australia, the species seems only to be present on some offshore islands in the north and north-west. The species seems to have originated in the Lesser Sunda Islands in Indonesia and to have been spread eastwards and westwards by early human settlers.

This species varies very much in size and pelage, resulting in some taxonomic confusion, but as a general rule it is larger in the eastern Pacific islands than in its western range, and some authors prefer to divide it into at least two subspecies: *R. e. exulans* to the east and *R. e. concolor* as the mainland type. The rat is small, with a body weight of no more than 60–80 g, and it measures 120 mm long when fully grown, with a tail of about the same length. Its renal efficiency is greater than that of the brown and roof rats, and it thrives well in rural areas with poor water resources. A characteristic phenomenon is that the species is more commensal in its western range than in New Zealand and the Pacific islands.

The Polynesian rat is considered an unspecialized species (Brooks and Than Htun, 1980), an advantage for a commensal rodent. It is a major pest in buildings all over Thailand, Myanmar, Vietnam and Cambodia. Apart from also being an important agricultural pest, it is also considered a problem on certain islands because of its predation on protected vertebrates such as the tuatara (*Sphenodon*) and other reptiles and ground-nesting birds. The species is regarded as a principal mammalian reservoir of plague in certain parts of its distribution range, as it is highly resistant to *Yersinia pestis*, although it is quite easily infected. It has also been found to carry leptospirosis (including *Leptospira icterohaemorrhagiae*) and murine typhus, facts that have to be correlated with its close connection with man.

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3 Rodents in Agriculture and Forestry

B.J. Wood[1] and G.R. Singleton[2]
[1]*Merrivale Research, Exton Lane, Exeter, UK;* [2]*International Rice Research Institute (IRRI), Metro Manila, Philippines*

Introduction

Rodents occur in virtually every terrestrial environment that supports life, be it wild, agricultural or urban. Many species comprise relatively small individuals with the capacity to multiply rapidly. Generally, rodents are omnivorous, feeding mainly on plant materials, which may include seeds, leaves, roots, whole young plants, fruit, grain and tree bark; and animal tissue, for example, insects, snails, other invertebrates and the bodies of vertebrates. They may also feed on living plants and animals, and by scavenging. Some species are fairly restricted in diet, but most are quite versatile, and some can adapt readily to manufactured food products and wastes. Many species are fossorial, nesting and living much of the time in burrows; others live at ground level, progressing through tree climbing to completely arboreal species. Rodents are represented in all climatic zones from Arctic tundra to the equatorial tropics, and they include species that are well adapted to arid conditions. In common with most taxonomic groups, rodents show a tendency to having a greater number of species in warmer, wetter environments. All of these characteristics predispose rodents to live freely in competition with humans (i.e. to be pests), including their role in important depredations in agriculture (broad sense), an overview of which is the theme of this chapter.

Since the previous edition of the book, work in other regions, in particular China and Africa, has intensified and become accessible to an international audience. There has been wider awareness of the environmental factors that regulate population sizes, and how to amend the situation to minimize the threat, an approach that has crystallized as 'ecologically based rodent management' (EBRM). Much of this is covered in three multiple-authored works, all edited by Singleton *et al.* (Singleton *et al.*, 1999a, 2003a, 2010a). This chapter aims to be a guide to the recent literature. Inevitably, it is selective, with a high proportion of the citations from reviews.

The accounts given are divided by geographic region and then further subdivided, in some cases, by specific crop. Rice receives wide coverage, as justified by its importance as a world food source, and because it is undoubtedly subject to very heavy and not always fully recognized losses to rats.

Species Involved

Pest species are to be found among the three major suborders of rodents, the Myomorpha (rats, mice, voles, hamsters, gerbils, jirds, mole rats), the Sciuromorpha (the squirrel-like rodents), and the Hystricomorpha (porcupines, cane rats and other, usually larger, rodents). The species complex infesting a particular agroecosystem varies according to geographical location and type of habitat. Broadly, these are temperate, subtropical or tropical, and whether they are wet or arid. Whereas there are variations in species between the large land masses, there is a tendency towards analogous types, more or less closely related biologically, in corresponding environments.

Altogether, relatively few of the large number of known rodent species have become pests. Southern (1979) (citing Morris, 1965) mentions 1729 rodent species, but only 125 are reported as pests in this chapter. This rather small proportion applies just as much to the tropics as elsewhere. Thus, Delany and Happold (1979) list 240 species in 12 families in Africa, but two myomorph species (or species groups) are by far the predominant pests (namely, *Arvicanthis niloticus* in the north and *Mastomys* (*Praomys*) *natalensis* in the south), with just a few others in specific circumstances. In Malaysia, Medway (1978) listed 19 species of *Rattus*, but only four or five have become significant pests of agriculture. Some of the non-pest species are now assigned to other genera (Payne *et al.*, 1985; Francis, 2008). Records from China give 168 species of rodents in 14 families (Wang and Deng, 1984) but only a few have become pests.

In this account, biological names (Ellerman, 1941, 1949) are given, favouring the names used in the articles cited. Internet sources, including Wikipedia, have also sometimes been used. Common names are mentioned where they are widely used. The taxonomic affinities of the rodent genera mentioned in the chapter are summarized in Table 3.1.

Table 3.1. A listing by suborder and family of the rodent genera mentioned in this chapter.

Suborder	Family	Subfamily (where relevant): Genus
Hystricomorpha	Abrocomidae	*Abrocoma*
	Hystricidae	*Hystrix*
	Myocastridae	*Myocastor*
	Octodontidae	*Octodon*, *Spalacopus*
	Thryonomidae	*Thryonomys*
Myomorpha	Cricetidae	Arvicolinae: *Arvicola*, *Myodes* (= *Clethrionomys*), *Lagurus*, *Lemmus*, *Microtus*, *Neofiber*, *Ondatra*, *Pitymys* (subgenus of *Microtus*)
		Cricitinae: *Cricetulus*, *Cricetus*
		Neotominae: *Peromyscus*
		Sigmodontinae: *Eligmodontia*, *Holochilus*, *Oryzomys*, *Sigmodon*
	Gliridae	*Glis*, *Graphiurus*
	Muridae	Deomyinae: *Acomys*, *Uranomys*
		Gerbillinae: *Meriones*, *Tatera*
		Murinae: *Apodemus*, *Arvicanthis*, *Bandicota*, *Berylmys*, *Chiropodomys*, *Dasymys*, *Hylomyscus*, *Lemniscomys*, *Lophuromys*, *Mastomys*, *Melomys*, *Millardia*, *Mus*, *Nesokia*, *Niviventer*, *Oenomys*, *Praomys*, *Rattus*, *Rhabdomys*, *Stochomys*
	Nesomyidae	Cricetomyinae: *Cricetomys*
	Spalacidae	*Cannomys*, *Myospalax*, *Rhizomys*, *Spalax*
Sciuromorpha	Geomyidae	*Thomomys*
	Heteromyidae	*Perognathus*
	Sciuridae	*Callosciurus*, *Citellus*, *Cynomys*, *Eutamias*, *Funisciurus*, *Funambulus*, *Marmota*, *Paraxerus*, *Sciurotamias*, *Sciurus*, *Spermophilus*, *Tamias*, *Xerus*

Incidence of Rodent Problems

In temperate zones, rodent pests of pasture and field crops originate mainly from grassland species, and those of forestry and orchards mainly from woodland species. Numbers tend to be cyclic, increasing in the growing season and declining in winter. There can be big variations between years.

Much the same broad ecotype subdivisions occur in warm temperate and subtropical climates, but population fluctuations are generally less. Arid conditions may involve regular but short and sparse rainy periods. Rodents adapted to arid environments can be damaging to any crops grown in them. In the equatorial tropics, the steadier climates tend to be continuously conducive to rodent increase. Population numbers may fluctuate in response to rain and crop seasons, but in perennial crops tend towards relative stability. Highland tropics share some of the features and species of both subtropical and tropical environments.

Often, certain species become closely associated with particular crops, especially those that provide all the requirements for a species to complete its life cycle when the crop is grown on a large scale. This leads to another broad distinction, that between resident rodent pests, those of regular seasonal incidence and those of periodic invasions.

This ecological perspective is evaluated further in the Synthesis section towards the end of the chapter (see also Chapter 1). It is key to evaluating loss potential from a rodent pest, and to developing control measures and implementing the methodology, which is covered further in Chapters 5 and 6.

Temperate Regions – Pasture and Field Crops

Rodents adapted to open environments affect pasture in various ways, the most direct being grazing, which cuts back plants and seedlings, the destruction of roots and the reduction of seed regeneration. Grazing does not always give a dramatic impression of loss, but it can be a steady drain on carbohydrate reserves, limiting growth and, at crucial times, reducing winter survival and nutrient value, and posing competition with livestock. Field crops may suffer direct loss of the utilized part (fruit, leaf, corm, etc.), but often the effect is indirect (e.g. reduced stature, quality or competitive ability against weeds).

Northern Europe

Rodent outbreaks have been known in European agriculture from prehistory, and severe crop damage is still common (see Pelz, 2003 for reviews; and Jacob and Tkadlec, 2010). Incidence is strongly cyclic, depending on fluctuating environmental factors, with a gradation away from locations with more marked winters. Rodents sometimes reach plague proportions; for example, in Hungary in 1964–1965, the common vole, *Microtus arvalis*, caused extensive damage in most cultivated fields despite control efforts covering 3.6 million ha, which proved to be too late (Myllymäki, 1979). The most serious depredators in grassland include *M. arvalis* in east and interior Europe, and the field vole, *M. agrestis*, in north-west Europe (Jacob and Tkadlec, 2010). The former can reach very high populations, recording over 2000 ha^{-1} or much more on occasion. *M. agrestis* generally occurs at a density of 100–400 ha^{-1}. Where their ranges overlap, *M. agrestis* is mainly a woodland species. The bank vole, *Myodes glareolus*, across the region generally peaks at about 100 ha^{-1}, exceptionally going to 400 ha^{-1}. *Arvicola terrestris* is now split into *A. scherman*, a fossorial species that increases up to a density of 100 ha^{-1} in dry grasslands and meadows in central and eastern France and west Switzerland, but can reach 1000 ha^{-1}, and *A. amphibius* in floodplains in eastern Europe.

In grasslands, huge areas may be attacked. The rodents cause yield loss, growth of contaminating weeds, soil contamination of the cut crop, and reduced quality with an ongoing effect on stock. In field crops, clover, lucerne, winter cereals and rapeseed are damaged by voles; the extent of the damage is highly correlated with rodent density, and can cover areas of hundreds of thousands of hectares. Losses have been recorded of 80% of lucerne, 50% or more of wheat and, exceptionally, have reached 100%. Attack may extend to sugarbeet and vegetables in peak population years.

Severe damage can be caused to sugarbeet by the wood mouse, *Apodemus sylvaticus* (Pelz, 1989). This problem arose with the widespread adoption of precision drilling of seeds according to final density requirement. The mice detect the seeds by smell and dig them out. The problem is widespread in Germany (Pelz, 1989), in the UK (Anonymous, 1980) and in Belgium (Moens, 1988). Wide variations in damage occur, with complete resowing needed in some years. Serious damage is most likely either if the crop is sown early or too shallowly when the *A. sylvaticus* population is still relatively high, or when low temperatures delay germination and seedbeds are dry. It appears to be less related to variations in population size or any obvious environmental factor. In this case, damage control can be achieved by diversionary feeding. Pelleted seeds are applied to the surface and the mice feed adequately with less expenditure of energy than by digging up seeds, for the brief susceptible period (Pelz, 2003). Lethal control, if required, is by use of anticoagulant baits, with some attempts to reduce population pressure by modifying source vegetation conditions.

Recently introduced species sometimes cause problems. Examples are two species brought to Europe for fur production. The coypu, *Myocastor coypus* (from South America), which escaped into wetland habitats in Britain, caused extensive damage to field crops and water systems by its burrowing, and the muskrat, *Ondatra zibethicus* (from Canada), behaved similarly in continental Europe (Gosling and Baker, 1989).

Southern Europe and Eurasia

M. arvalis is replaced in southern Europe by *Pitymys duodecimcostatus* and other species that do similar damage, especially to horticultural crops, but with less frequent or intensive plague cycles. In some regions, the common hamster, *Cricetus cricetus*, severely damages cereals (Giban, 1962). The Levant vole, *Microtus guentheri*, is the main rodent pest of field crops in south-east Europe and the Near East. It is cyclical in abundance, reaching plague proportions in some years, something that apparently depends on the crop seasons. In one case, a large-scale lucerne planting created after swamp drainage, and thus without marked annual or seasonal fluctuation in food abundance for the voles, had regular losses of up to 50% (Myllymäki, 1979).

Moving eastward, various analogous pest species occur. These include *M. socialis* in the south-west of the USSR, the steppe lemming (*Lagurus lagurus*) to the east, *M. gregalis* in south Siberia and *M. fortis* further east. Several ground squirrels (*Citellus* spp.) assume importance in the steppe region. These appear to be analogous to the ground squirrels of the prairies of North America, which are discussed later in this chapter.

China

Grassland occupies some 2.8 million km^2 across northern China, the largest area in the world, but it produces only 8% of total domestic meat and 25% of wool needs. Further, the ratio of production to unit area involved is only 10–20% of that in more developed regions. Much of the limitation is from rodent depredation, from particular species in each region, and from pikas (Daurian and plateau pikas), which are lagomorphs, but because of their size and behaviour have been described as 'honorary rodents' (Zhang *et al.*, 2003c).

In Inner Mongolia (NE China), Brandt's vole, *Lasiopodomys* (*Microtus*) *brandti*, can affect up to 20 million ha (75% of the region) (Zhong *et al.*, 1999; Zhang *et al.*, 2003c). There is a clear relationship of increasing numbers to overgrazing. Wild vegetation, a mixture of grasses and some 'weeds', supports a relatively small population of such rodents as *Cricetulus barabensis*, *Citellus dauricus* and the Daurian pika (*Ochotona daurica*). These cause losses of around 10–20% of potential grass production, and require constant monitoring. However, when grazing is too intensive (which is the tendency, in order to try to increase current production), the vegetation character changes in composition, coverage and height. As the height goes below 10–20 cm, the dominant vole species becomes Brandt's vole. Once Brandt's vole populations build up, the depletion of vegetation is increased, so favouring further increase. The vole can eat 40 g of fresh material a day, and populations can go to well over 1000 ha^{-1} (Zhong *et al.*, 1999), while the complicated burrowing systems lead to soil instability. Numbers can fluctuate considerably between years, from both the direct and indirect effects of climate variation and the effect of prevailing population numbers on future populations (Pech *et al.*, 2003). In more infested years, over 5500 holes ha^{-1} have been found (Zhong *et al.*, 1999), and the relationship between number of holes and increasingly lower height of vegetation is consistent. Overall, the increase in livestock grazing since the 1950s has led to more years when the balance of grazing and plant growth favour Brandt's vole, leading to an increase in the frequency of outbreaks of the vole populations (Zhang *et al.*, 2003b). On top of this are population changes associated with climate (Southern Oscillations) – rodent densities are higher in an El Niño year and 2 years thereafter, and also in the first year after a La Niña event (Jiang *et al.*, 2011).

Eventually, damage from loss of vegetation and burrowing can be so intense that high erosion and desertification occurs. At this stage, the Mongolian gerbil (*Meriones unguiculatus*) becomes the dominant pest of overgrazed grasslands; this species is also an important reservoir for human diseases (Zhang *et al.*, 2003c).

In Qinghai province (north central China) eastward to Tibet there are about 140 million ha of alpine meadow, and 20% of the area is degraded (Fan *et al.*, 1999). Two species especially are responsible, the plateau pika (*Ochotona curzoniae*) and the plateau zokor (*Myospalax baileyi*). They both compete for livestock grazing, with the total loss broadly estimated at the equivalent of 150 million sheep, while their burrowing further destroys vegetation and soil structure. They occur in separate places, with zokors found in lower lying areas, but like Brandt's vole, both build up in shorter less grassy vegetation, which Fan *et al.* (1999) refer to as a vicious circle – the damage further increasing the suitability of the grassland for further build-up. Eventually, this can result in severe erosion and desertification, even contributing to sandstorms at great distances (Zhang *et al.*, 2003c). In a studied area of 3.7 million ha in Qinghai Province (Fan *et al.*, 1999), about a third was affected by pikas and 12% by zokors. An investigation showed that as overgrazing occurred, so the population shot up, the pika from nothing to 200 ha^{-1} and the zokor by three to four times, up to more than 40 ha^{-1}. The number of pika holes showed a clear relationship to decreasing height of vegetation, with none at 85 cm, 4 ha^{-1} at 70 cm, 25 ha^{-1} at 9 cm and 43 ha^{-1} at 2 cm. Zokors additionally cause loss by heaping soil into mounds that can bury the grass. Pikas, like the Brandt's vole, show marked fluctuations in numbers from year to year, whereas the zokor varies less, perhaps because its habitat is more protected from environmental fluctuations.

The mechanisms for the increases in population in these rodents as vegetation height decreases seem complicated. As populations build up, the density of grass decreases, but there are also density-dependent factors regulating populations. Pech *et al.* (2007) examined the rate of recovery of populations after chemical knock-down and also the effect of exclusion of livestock from grasslands using fences. Although populations were reduced by up to 90% when chemical control was implemented in the spring, there was a rapid population recovery in summer, leading in the autumn to similar population densities and grass biomass as with the control operations. The effect of preventing grazing by large mammals led to better winter survival of pikas. In a study of zokors (Fan *et al.*, 1999), grass and sedge yield decreased proportionately with increase in density, but weed yield did not change much. All of the dominant rodents appear to feed on certain weeds, which may satisfy some specific dietary need. For Brandt's vole (Pech *et al.*, 2003), more open conditions may include easier social interaction among voles and less protection for predators. Fruits of the sagebush, *Artemisia frigida*, feature particularly in their overwintering food stores (Zhong *et al.*, 1999). Plateau pikas and plateau zokors are both considered pests by local herdsmen, but the evidence suggests that overgrazing by yaks and sheep is the main factor influencing meadow grass biomass. Indeed, there is emerging evidence that pikas and zokors are keystone species in these grasslands and play an important role as ecosystem engineers (Smith and Foggin, 1999; Zhang *et al.*, 2003a).

In summary, for the grasslands of both Inner Mongolia and the Qinghai–Tibet plateau, short-term control of the dominant small mammals can be achieved by poison baiting, but generally, population recovery is rapid. The most sustainable approach is to control grazing stock to appropriate intensities by fencing and movement restriction. This allows cover height to go above that critical level for expansion of the rodent numbers. Thus, in one trial, Brandt's voles were at a density of 80–150 ha^{-1} with exclusion from mid-May, but at 500–560 ha^{-1} with the traditional timing from mid-June. Very degraded areas can be restored by poison baiting and then a period of severely reduced grazing, such as complete exclusion for one (annual) season and firm limitation for the second. Herbicides can alter the weed balance to disfavour the rodents (Zhong *et al.*, 1999).

In Xinjiang Province (far NW China), the Xinjiang lemming (*Lagurus luteus*) is the most serious pest of the extensive grasslands (Zhang *et al.*, 2003c). This fluctuates in a fashion associated with lemmings in general, reaching very high numbers every 4–5 years, and then dying off. Damage can be severe in peak years, with 2080 holes ha^{-1} mentioned.

Arable crops in the temperate zone of northern China suffer severe attack from a range of rodent species, depending on the agricultural practices and the nature of surrounding vegetation. The rodents do damage by direct feeding, by deep and extensive burrow systems, and by collecting seeds and seedlings for winter storage. External changes, such as increasingly extreme winter to summer differences, and cultural techniques like the reduction of flood irrigation that incidentally helps to control burrowing species, appear to have the potential to worsen problems.

Various studies on rodent management in Chinese agroecosystems have been carried out (Zhang *et al.*, 1999). In the North China Plain (Hebei and Shandong provinces), winter wheat is sown, with maize after harvest, as a summer crop, and with plantings of a range of such crops as groundnuts and beans. An important pest is the ratlike hamster, *Cricetulus triton*. Its burrows are a chief source of damage, and control may be practised by digging out the burrows – when large stashes of grain may be recovered. Flooding can greatly reduce incidence; in one district, this species gained predominance from the striped field mouse, *Apodemus agrarius*, when sprinkler irrigation replaced flood irrigation. Novel traps have been developed. Intensive area-wide baiting can reduce numbers but recovery is rapid, but this can apparently be slowed down by application of chemosterilants (Chapter 5). In the North Loess Plain (Shanxi and Shaanxi provinces), the Chinese zokor, *Myospalax fontanieri*, attacks maize and winter wheat. This species is difficult to bait or trap, and a method of control by burrow fumigation, or application of 'explosive paper strips' in burrows, can reduce populations, as can the more ecologically based removal of supporting vegetation from the adjacent non-agricultural areas and the planting of toxic plants. In the southern part of Inner Mongolia, the Mongolian gerbil will attack arable crops, doing severe damage to cereals and potatoes.

North America

About half the world's known vole species are indigenous to North America, and some are pests of pasture and field crops. They are of little importance on the eastern side of the continent, though *Microtus pennsylvanicus*, a common forestry and orchard pest, sometimes extends into field crops.

Major outbreaks of this and other species, such as *M. drummondi*, have been recorded in central USA and found to consume more herbs on the northern prairies than any species of large herbivore. In California, *M. californicus* and *M. montanus* become serious pests in the peak years of the 4–6 yearly cycles, spreading into crops from uncultivated grassy patches (Clarke, 1984). They burrow in fields of lucerne, eat the leaves, stems and roots of the plants, and leave large dead patches. They extensively destroy root crops below the ground before the damage becomes noticeable, and they graze cereals. Generally, numbers decline at harvest, with some survival in surrounding source vegetation. In a review of rodent outbreaks in North America, Witmer and Proulx (2010) noted that in Washington State *M. montanus* and *M. longicaudatus* build up markedly in no-till agriculture, when residual vegetation provides food and shelter. They continue to be active in winter under snow, feeding on roots, tubers and grain crops.

Pocket gophers (*Thomomys* spp.) are burrowing rodents that reach 15–30 cm in length and cause considerable damage to rangelands and field crops by feeding, subterranean hoarding of plant tissues and soil disturbance. They are active throughout the year and may be considered the most important rodent pests in some western states (see, for example, Lewis and O'Brien, 1990). Loss of range vegetation is estimated at up to 20%, but these species need broadleaved food as well as grass to survive.

Sciuromorphs are more serious pests than myomorphs in the prairies of Canada down to central and western USA, and also spread into field and horticultural crops (Marsh, 1984). They are diurnal and tend to be larger than the myomorphs (range 400–1200 g), so are more noticeable. Among about 20 species of ground squirrels, *Spermophilus* spp. are the most important. *S. richardsonii* has been a noted pest for many years (Witmer and Proulx, 2010). It reaches a weight of 450 g and lives colonially in extensive burrow systems. It feeds on a range of crops, and is most successful when vegetation is of short stature. Thus, it built up markedly in a period of drought in 2000–2001, reaching densities of over 40 ha^{-1}. Subsequent overgrazing prolonged the problem. Attempts at control by baiting were uncoordinated and largely ineffective. Prairie dogs (e.g. *Cynomys ludovicianus* and *C. gunnisoni*) are somewhat bigger, are more colonial and do not hibernate. Populations can reach 250 ha^{-1}, although generally 50 ha^{-1} is considered high. They too appear to be favoured by the effects of grazing stock. Several million hectares of rangeland can potentially be infested, but control measures influence the actual affected area from year to year.

In broad economic terms, about 350 Columbian ground squirrels (*S. columbianus*) consume as much as one sheep, and about 200 Californian ground squirrels (*S. beecheyi*) are equivalent to a steer. Six of these squirrels in a 0.2 ha pen reduced annual forage production by 1184 kg ha^{-1}. The Zuni prairie dog, *C. gunnisoni*, can destroy 80% of available forage and 300 individuals eat as much as a cow (Marsh, 1984). Among extensive damage to other crops, Sauer (1984) found that ground squirrels, predominantly *S. beldingi*, reduced lucerne crops by an average of about 1200 kg ha^{-1} of the first cuttings, or 25% of the potential yield. Severe damage to cereals also occurs when high populations spread as grasslands dry up.

Marmots (*Marmota* spp.) inhabit open woodland or shrub vegetation and become agricultural pests around harbourages such as creeks, ravines and other uncultivated patches. They hibernate and their distribution is patchy. In the crop-growing season, individuals can reach a weight of 2.5 kg and eat about 500 g of green vegetation a day. The loss of cereal and forage crops in particular is compounded by the trampling and clipping of vegetation not consumed.

Australia

The introduced species, *Mus domesticus*, has become a major problem to agriculture in South Australia. It erupts in plagues, which occur in years when suitable early summer rains keep soils moist (Brown *et al.*, 2010); see also Chapter 1.

Temperate Regions – Forestry and Orchards

Rodents cause serious economic losses in forestry and orchards. The preadaptations required for living in woodland generally lead to a different complex of species from that occurring in grassland and field crops. The worst damage is by bark stripping, either ring barking at ground level (mainly by fossorial species), on the main trunks (ground dwellers) or in the branches (climbers). Complete ringing causes the distal part of the tree to die, and when damage is low down this can mean death of the whole tree. Wounds also permit the establishment of bacterial and fungal infections, which stunt growth and flaw the timber product.

The reasons for debarking have been the subject of conjecture by several authors. Such damage to 10–40-year-old beech, sycamore and oak in Britain by *Sciurus carolinensis* has been studied in detail (Kenward, 1989), and seems to have general implications. The squirrels strip the bark, scatter it and then eat the sap-filled phloem beneath. Damage varies greatly between years but is not closely correlated with the size of the population of adult squirrels. It appears that heavier damage is more likely in years following those when a high number of young are born and when, in the competition to survive and establish themselves, some discover this food source during exploratory behaviour. Trees with a phloem layer thicker than 0.3 mm are mainly affected. Below this thickness, there is no further damage after an initial probing. Phloem is not a rich food source and damage intensity does not correlate with food shortage. In fact, from year to year, squirrel density appears to be related to the amount of seed fall. *S. carolinensis* is a fairly recent introduction into Britain, which has rapidly displaced the native red squirrel, *S. vulgaris*. It does not cause this tree damage in its native North America, perhaps because, in the mainly self-set forests there, trees rarely have phloem layers more than 0.3 mm thick, which appears to reflect an evolutionary association.

Other types of rodent damage to trees include the grazing of young trees, root destruction and seed eating (Gill, 1992a,b). These appear to be more 'normal' feeding activities. Generally, very young trees have a higher nutritional value than mature trees and are preferred by small rodents, which kill many trees; those that are injured may be weakened, or set back competitively, remaining inferior in size and often in shape as well. Golley *et al.* (1975) quote 78% losses of deciduous seedlings to the yellow-necked mouse (*Apodemus flavicollis*) in eastern Europe. Only 6–7% of more mature fast-growing trees died, although 48–67% of the trees were damaged at the roots by *Microtus oeconomus* in Poland. Bark is stripped from the branches of older trees and there may be complete ring barking. Such damage is most common where snow cover prevents access to seedlings. Root bark may increase in winter, and be associated, inter alia, with an increase in sugar levels in the bark (Pelz, 2003). Seed depredation is common in forests, though assessments of its importance vary. It is most likely to cause economic problems where direct seeding is practised.

Some tree species are preferred by rodents, or are more affected by their damage, and some seeds are selected. Thus, rodents can affect species composition in naturally regenerating forests. Rodents also feed on tree fruits, but this tends to be by species more associated with field crops than those adapted to woodlands.

After clear-cut logging, there is generally a rapid growth in understorey vegetation, which forms suitable conditions for a build-up of rodents. These can pose major problems for newly planted tree stock, especially of saplings from nurseries rather than the seedlings that were used previously. Several of the field rodents of North America, for example, have been implicated (Witmer and Proulx, 2010).

Attempts at control generally are by poison baiting, but the relationship of other vegetation to population size indicates the need for greater attention to an ecological approach.

Europe and Asia

Natural woodlands and forest plantations are an important resource in much of north

Europe. They are damaged by the field vole, *M. agrestis*, and to a lesser extent by the bank vole, *Clethrionomys glareolus*. In the vast commercial forests of Fennoscandia, increased losses in recent decades appear to be associated with the replanting of natural woodlands, mostly with coniferous forests, thus opening up the canopy.

It can be difficult to get some tree species established and this has affected forestry policy. For example, in Finland in the 1950s, hybrid aspens were widely planted but, because few survived to be harvested as a result of attack by *M. agrestis*, this practice declined. In Scots pines, the voles destroyed cuttings from clones intended as seed parents. Vole populations build up through the growing season and collapse in winter. They achieve differing abundance from year to year, with a cycle of about 2–4 years. Forests are Finland's most important natural resource, and the effects of voles on pines, spruces and birches, the most important tree species, were investigated between 1973 and 1980 (Teivainen, 1984). About 720,000 ha were reafforested, and 90,000 ha of farmland were allowed to revert to forest. Vole damage affected 2100 plantations, or over 7.4 million young trees. Although the incidence of damaged trees averaged only about 0.2% in reforested and 3% in reverted farmland, it rose to 30 or 40% in individual cases. This discouraged the reafforestation of farmland, and between 1969 and 1982, 200,000 ha were left fallow and grassy.

Damage from *M. agrestis* and *C. glareolus* is common in north-west and central Europe, often extending over several thousand hectares (Golley *et al.*, 1975; Myllymäki, 1979). Moving from this region, *M. agrestis* is replaced by other species; for example, *M. oeconomus* in Poland, *M. socialis* further east and *M. guentheri* in the Middle East. Other microtine species occur across eastern Asia, as far as Japan. Water voles, *Arvicola* spp., have the potential to attack woodlands in the breeding season. Occasional instances of severe damage are reported but these are limited where the ground vegetation is kept back. The edible dormouse, *Glis glis*, damages trees by debarking throughout its range in Europe, e.g. in Italy (Santini, 1987), including in patches where it has recently established itself (Gill, 1992a).

In China, reafforestation with red pine is often impossible owing to damage by the grey-sided vole (*Clethrionomys rufocanus*), *S. vulgaris* and the Siberian chipmunk, *Eutamias sibiricus* (Deng and Wang, 1984). Pallas's squirrel or the red-bellied tree squirrel, *Callosciurus erythraeus*, strips bark, reduces timber value and often kills the exotic conifers planted in place of native species. Squirrel numbers build up in the spring, when most damage is done, reaching 2.5 ha^{-1} in forests of the Japanese cedar, *Cryptomeria japonica*. Cypress is also damaged, probably by *A. agrarius* (Howard, 1985). *C. rufocanus* causes similar damage in Japan (Nakatsu, 1987). In China, trees commonly are planted to limit erosion, with some preference for species with a product of commercial value, such as the wild apricot, *Prunus armeniaca*. A study in north-east China (Hebei Province) (Li and Zhang, 2003) found establishment to be much restricted by seed predation by a large number of rodent species, including the white-bellied rat (*Rattus confucianus*), *A. agrarius*, *C. triton*, the grey-sided vole, *C. barabensis*, the long-tailed hamster (*C. longicaudatus*), the chipmunk (*Tamias sibiricus*), the red-backed vole (*C. rutilus*), and the grey squirrel (*Sciurotamias davidianus*). The field mouse (*Apodemus speciosus*) was commonest, and showed the largest consumption of seeds in captivity. The apricot may be considered for establishment in existing forest, scrub or open areas. Seed disappearance was more complete under canopies with more exposed ground than it was in the open with a grass sward. Possibly this is because the seeds are harder for the rodents to find in a sward, and such areas are recommended for easiest establishment of the apricot.

Among orchard pests, *M. agrestis* can cause serious economic damage in Swedish orchards. In central Europe, *M. arvalis* debarks fruit trees and *A. terrestris* can inflict serious damage locally. For example, in what was then East Germany, 650,000 apple trees were destroyed from 1958 to 1963.

In southern Europe, *Pitymys duodecimcostatus* attacks apple, peach and cherry orchards, feeding on roots and girdling stems at ground level (Guedon and Combes, 1990).

North America

In North American forestry in the east, the meadow vole, *M. pennsylvanicus*, has a pattern of occurrence and damage similar to that of *M. agrestis* in Eurasia, but is less important because reafforestation is mainly by direct sowing (Myllymäki, 1979). Pocket gophers (*Thomomys* spp.) are the most important forestry pests. They chew roots, graze and debark conifers, including the aerial parts when there is snow cover. In 1988, 64% of forests were reported to be damaged by these animals (Borrecco and Black, 1990). Anthony and Barnes (1983) found correlations between signs of activity, population size and damage to conifers by *T. mazama* in Oregon and California, and by *T. talpoides* in Idaho. Other forest rodent pests debark the aerial parts of large trees; these include *Sciurus griseus* (Baldwin *et al.*, 1987) and ground squirrels. Beavers and porcupines can cause localized damage, including the destruction of established saplings. Conifer seed predation by *Peromyscus maniculatus* can adversely affect reafforestation efforts (Sullivan, 1987; Witmer and Proulx, 2010).

Further south, pine forest pests include those of the above groups and the pine vole (*Microtus pinetorum*), field mice (*Peromyscus* spp.) and the hispid cotton rat (*Sigmodon hispidus*) (Jackson, 1990). Loss estimates inevitably tend to be generalized because forests are widespread and diffuse, and the damage potential varies between localities and times. An estimate of the cost of annual losses caused by mammals, of which rodents are the most important, was US$1.83 billion in the late 1970s. This broadly indicates the significance of rodent damage (Seubert, 1984).

Throughout North America, microtine rodents are the most important pests of temperate orchards. These include the meadow vole in the more northerly areas, and the pine vole, *M. pinetorum*, further south. In the west, *M. pennsylvanicus*, *M. montanus* and *M. longicaudus* are commonest in the north and *M. californicus* further south, attacking citrus, olive and cherries.

The pine vole tunnels under orchard trees and feeds on their roots. Attacked trees may suddenly die. If pine voles are controlled, meadow voles may replace them. Damage occurs every year but uncontrolled populations typically show 2–4 year cycles of abundance (Kaukeinen, 1984). High crop yields are necessary for profitability, so the economic damage threshold is low. Even a single animal directly under a tree can render it non-productive and, on average, damaged trees lose about 40% of their potential production.

In the late 1970s, losses in the eastern apple crop were estimated at about US$50 million (Seubert, 1984) and, in 1975, about 6% of the crop was lost (Kaukeinen, 1984). Over 50% of orchards in Washington State are regularly damaged by *M. montanus*. In 1985/6, 82% of apple-bearing and 57% of immature trees were damaged in two valleys comprising 65,000 ha, with large amounts of bark removed. Vole populations reached 4200 ha^{-1}, causing losses of about 36% of the crop in the first year, with an almost similar value loss for tree replacement.

Other regions

In Chile, Murua and Rodriguez (1989) noted bark gnawing by *Eligmodontia typus*, *Octodon degus*, *Octodon bridgesii*, *Spalacopus cyanus* and *Abrocoma bennetti* among native and exotic forest trees. Up to 55% of stems were attacked in over 1 million ha of plantations established from 1974 to 1989.

Subtropical, Highland Tropical and Arid Regions – Grassland and Field Crops

In these regions, field crops are grown on a scale varying from smallholder (village) level to large-scale farms. Often, climate limitations greatly restrict productivity, particularly in drier areas, where it may be possible to grow crops only at subsistence level, unless irrigation is available. To a large extent, population fluctuations depend on the vegetation changes brought about by rainfall seasons and quantities. Numbers and species composition will shade from wetter to desert zones, while the crops in irrigated areas within dry zones attract rodent pests.

Europe, North Africa and Asia

There is a broad band of territory south of the European and Asian temperate regions, stretching across North Africa, Asia Minor, Pakistan, India, Bangladesh and south China, in which a range of rodents attacks field crops. In the fertile regions of North Africa, particularly the area around the River Nile, the principal rodent pest of agriculture is the Nile rat (*Arvicanthis niloticus*). This attacks virtually all crops, including horse beans, soybeans, maize, fruit and vegetables, with losses estimated at 0.5–8%. It is a serious pest of cereals, particularly wheat, and damage in Egypt has been estimated at up to 20%. A conservative estimate of annual total losses in the early 1980s was US$60 million, despite control efforts (Greaves, 1987). In the eastern Mediterranean area, the Palestine mole rat, *Spalax leucodon*, feeds on the subterranean parts of most crops but, despite its importance as a horticultural pest, detailed quantitative estimates of losses are not readily available. The range of the short-tailed mole rat, *Nesokia indica*, a mainly subterranean feeder, extends from Egypt across to north India in cultivated fields and orchards (Agrawal and Prakash, 1992).

The lesser bandicoot rat, *Bandicota bengalensis*, is found from Asia Minor across to the South-east Asian tropics. It can be said to be the most important rodent pest of the Indian subcontinent. It attacks a wide range of vegetable crops, including the vegetative and fruiting stages of cereals, causing heavy loss, typically 20–40% in Pakistan (Greaves *et al.*, 1977). The soft-furred rat, *Millardia meltada*, attacks cereals in Pakistan and northern India. In India as a whole, several species of rodents occasionally feed on crops, but three are recorded as serious: *M. meltada*, the Indian gerbil (*Tatera indica*) and *B. bengalensis* (Barnett and Prakash, 1976; Chakraborthy, 1992a). Records are fragmentary, but losses often appear to be substantial (Prakash and Ghosh, 1992). The large bandicoot rat, *B. indica*, spreads into crops, although it is mainly a commensal (Chakraborthy, 1992b). Bangladesh has a short mild winter when various short-term crops can be grown, including wheat, which by the early 1980s had reached a planted area of over half a million hectares. *B. bengalensis* and *M. meltada* cause losses, with widely ranging estimates, commonly around 10% or more – for example, Poche *et al.* (1979) recorded losses ranging from 0 to 30%. Most estimates are for percentage cut stalks and not for actual yield comparisons with and without rat damage. Plants attacked include a range of fruit and vegetables, and also tropical crops. In the highlands in the north of the subcontinent, a range of niches is occupied by characteristic rodents that will damage most crop plants (Bhagat and Kaul, 1992; Sheiker *et al.*, 1992). The crested porcupine, *Hystrix indica*, particularly attacks subterranean crops such as potatoes and root vegetables. The northern palm squirrel, *Funambulus pennanti*, occurs across the region and also has a broad diet of crop plants (Prakash *et al.*, 1992).

In the subtropical area of south China, *B. indica* and *Rattus losea* are the principal pests of field crops (Deng and Wang, 1984). Rice grown in these seasonal climates can be subject to severe rodent attack (Zhang *et al.*, 1999), though this seems less consistent than in the equatorial wet tropics. In the Yangtze River basin in Hunan Province, the oriental vole, *Microtus fortis*, overwinters on river islands, and moves out into rice fields as they flood. Damage intensity varies between years, and control approaches include prediction by trapping, and short-term or even permanent fences and walls. In the Pearl River Delta (Guangdong Province), *R. rattoides* and *B. indica* overwinter in wild vegetation and orchards of banana and oranges. They damage rice and various vegetable crops. Poison baiting as the rodents move to the rice can kill them, but even at 90% elimination, complete recovery occurs in 4–6 months. Removal of the ground vegetation under the orchards gives good control, and this can be extended to the wild vegetation by planting orchard trees that have a dense canopy, such as lychee, mango and longan.

Taiwan is notable for its intensive agriculture, with patchwork multi-cropping rather than large monocultures. *Mus formosanus* and *A. agrarius* are the commonest rodent pest species in most crops, including cereals, vegetables and root crops, whereas *A. agrarius* and *R. losea* are common in legumes. However, the relative damage by each species has not been well studied, not even whether there is a consistent pattern. From a survey by Ku (1984), a very generalized estimate of potential annual loss was 200,000 t of agricultural product on the island.

Various gerbillines and jerboas become dominant pests in arid or desert environments from the west of northern Africa across to northern India. Damage to materials stored underground by both direct feeding and by soil disturbance are commonly reported (Myllymäki, 1979). Shaw's jird, *Meriones shawi*, damages cereals, in particular, across the whole of North Africa (Greaves, 1987). Loss estimates range from 10 to 100%. This is also the predominant pest of forage, field crops (including vegetables and groundnuts) and fruit trees (which it will also debark). The population fluctuates, with plague-scale outbreaks every 2–10 years. In still drier areas, the Libyan jird, *M. libycus*, can cause heavy damage to crops. Large immigrations from the desert are found to affect wheat grown under irrigation, and this species extends across to the Persian Gulf. Spiny mice, *Acomys* spp., are also common in the agricultural areas of Egypt, whereas *Mus musculus* has appeared in a similar way in a desert reclamation scheme in Egypt, causing an estimated 19% damage in barley and high losses in such crops as maize, peas, beans and horticultural crops. Tristram's jird, *M. tristrami*, becomes important from the eastern Mediterranean to western Iran.

In India, desert rodents move into areas where there is some water (periodic rain or irrigation) and cause economic loss by feeding on seeds, rhizomes, stems, leaves and flowers. *Meriones hurrianae* breeds throughout the year and is by far the most abundant mammal in deserts, reaching populations of 34–510 ha^{-1} (mean about 290 ha^{-1}). It has long-term population cycles and annual fluctuations in abundance that appear to be related to the amount of vegetation available for feed and the suitability of soil for burrowing. *T. indica* shows similar trends and habits (Barnett and Prakash, 1976). In the North Western Desert, a range of species occurs. In addition to *M. hurrianae* and *T. indica*, other murids are also frequent, including *Rattus meltada*, *Nesokia indica*, *B. bengalensis* and *Mus booduga*, the squirrel *F. pennanti*, and the porcupine *H. indica*. Apart from crop damage, the burrowing habit of desert rodents intensifies desertification from erosion by their loosening of soil (Tripathi *et al.*, 1992). The heavy pressure they exert means that no desert development programme can be undertaken without rodent management. All vegetable and pasture plants are at risk at all stages of growth, including as seeds, with a build-up for both local crop seasons. With the development of desert areas, changes in the rodent fauna may occur; for example, *M. hurrianae* is disadvantaged by soil cultivation or presence of irrigation canals that may favour *R. meltada*.

In China, *M. unguiculatus* is the commonest of a number of species inhabiting environments ranging from dry grassland to desert (Deng and Wang, 1984). It breeds throughout the year and, in favourable environments, may reach numbers of 200–300 ha^{-1}, although there can be marked fluctuations.

Sub-Saharan Africa

Most literature references for this region are to *Arvicanthis niloticus* (see Fig. 3.1), found in the Nile valley southward to East African countries and down to Kenya where its range intercepts that of *Mastomys* (*Praomys*) *natalensis*, which inflicts similar damage

(Taylor, 1984). Severe outbreaks occur at variable intervals, but much of the record is anecdotal (Odhiambo and Oguge, 2003). Individual studies and agricultural records provide some detail in specific cases, though there can be some uncertainty about species validity. *Mastomys* has recently been revised from six to nine species (Sicard *et al.*, 1999, citing Lavrenchenko *et al.*, 1988), and *Arvicanthis* from one to nine (Sicard *et al.*, 1999, citing Ducroz *et al.*, 1997). For present purposes, the name given in the particular literature cited is used.

In the higher lands of eastern Africa, the dominant cash and food crop is maize, which is subject to heavy rodent attack. Other cereals, legumes, tomatoes, root crops and cash crops like cotton and sugarcane also can be damaged (Makundi *et al.*, 1999). Losses have not widely been systematically documented but evidently can be severe, with grazing leading to total destruction of some plantings of wheat and other cereals, pulses and cotton. The digging up of seeds of newly sprouted maize, and the cutting down of young plants, can be particularly serious.

In Kenya, 90% loss can occur over large areas of maize. A trapping project (Odhiambo and Oguge, 2003) found six murids, of which *M. cf. erythroleucus* (possibly confused with *M. natalensis*) is most common (72% of trappings), followed by *A. cf. neumanni* (15%). Other species were *M. minutoides*, *Tatera cf. robusta*, *Lemniscomys striatus* and *Aethomys kaiseri*. In Ethiopia, a field trial compared the production of maize with and without rodent control. *M. erythroleucus* and *Arvicanthis dembeensis* were predominant, with *Tatera robusta*, *Graphiurus murinus* and *Mus mohamet* together making up less than 17% of captures (Bekele *et al.*, 2003). The proportions of the rodents involved varied according to ground vegetation and trapping method. In the rodent-proofed plots, 9.6% of planted seeds failed (seed predation or seedlings eaten), against 12.6% outside. However, yield was 26% lower without control, suggesting significant ongoing rodent losses to maize after the seedling stage.

Fig. 3.1. *Arvicanthis niloticus*, the Nile or African grass rat. This species is a serious pest of all aspects of agriculture and has a wide distribution throughout much of Africa, with the exception of the far south where it is replaced by rats of the genus *Mastomys* (*Praomys*).

In Tanzania, the main pest species of maize is *M. natalensis*. Reproduction continues throughout the year, while population fluctuations are closely linked to the annual rainfall cycle (Smythe, 1986; Telford, 1989; Leirs *et al.*, 1997). There are marked increases during the main rains in March and April, which is linked to the sprouting of the wild grasses and forbs that constitute the food supply of these rodents. Populations remain high until December, particularly if the November rain is adequate for further growth, but they then crash. Annual losses are estimated to be on average 15% (Makundi *et al.*, 1991), but in outbreak years can reach as high as 80%. Losses of 15% would result in loss of annual production of greater than 380,000 t, enough maize to meet the annual consumption of 2 million Tanzanians (Mulungu *et al.*, 2010). Estimated losses in invasive outbreaks in western Tanzania are 20% for maize, 34–100% for wheat and 34% for barley (Makundi *et al.*, 1999). Maize is traditionally grown in small plots within fallow land and permanent pasture. The factors that lead to population outbreaks of *M. natalensis* and keep populations in check in other years are well documented (Leirs *et al.*, 1996, 1997). The spatial distribution of losses at the seedling stage has also been documented, and the relationship between the density of rodents and their damage to maize has been described as sigmoidal, with relatively high losses at moderate densities (Mulungu *et al.*, 2005). The populations of *M. natalensis* would need to be reduced to less than 20 ha^{-1} to have a substantial impact on losses (Mulungu *et al.*, 2010). The ecologically based approach to rodent management has recently been extended to Swaziland and Namibia (Belmain *et al.*, 2008; Monadjem *et al.*, 2011; Mulungu *et al.*, 2011), with a stronger emphasis on postharvest management

At higher altitudes, grassland is affected by the zebra mouse, *Rhabdomys pumilio* (Makundi *et al.*, 1999), and in southern Kenya, maize is predated upon by the striped ground squirrel, *Xerus erythropus*. *R. pumilio* also inhabits the southern part of Africa (Taylor, 1984), and sometimes reaches high densities in cereal crops, feeding particularly on maize cobs. It is also a pest of plantations of young conifers in South Africa.

The rodent problem in West Africa (aside from the wet tropical region) is similar to that in East Africa, with marked differences in endemic species according to rainfall zone. *Mastomys huberti* and *A. niloticus* predominate in wetter areas, *M. erythroleucus* and *T. gracilis* where rain is strongly seasonal, and *T. petteri* in the most arid parts.

In both East and West Africa, larger rodents can be a localized problem, including porcupines (*Hystrix* spp.), the grass-cutter or greater cane rat (*Thryonomys swinderianus*) and the giant rat (*Cricetomys gambianus*).

In Madagascar (Duplantier and Rakotondravony, 1999), all the native rodents have disappeared or are restricted to the small remaining areas of native forest. Among the ubiquitous introduced commensals, the black rat, *R. rattus*, in particular, has become the major agricultural pest. In the highland areas, this species has a similar aetiology and causes similar crop damage to the range of rodent species in Africa in general.

In the arid regions of southern Africa, gerbils (mainly *Tatera* spp.) cause damage that is frequently noticeable but only occasionally severe (Taylor, 1984). The African striped ground squirrel, *X. erythropus*, also occurs in semiarid areas and causes damage of fluctuating severity to maize, particularly to the seeds and seedlings; the loss in southern Kenya averages about 10% (Key, 1990).

America

In southern parts of North America, extending into Central America, *Sigmodon hispidus* and *Oryzomys palustris* become a problem of field crops as well as of some large-scale tropical crops. Specific problems may arise in arid regions. For example, losses of 5–60% of jojoba beans (*Simmondsia chinensis*) in southern California are caused by pocket mice, *Perognathus* spp. *P. baileyi* was at one time the only species capable of surviving on jojoba seeds, but other species have apparently acquired a similar detoxification mechanism for the cyanogenic glucoside in the beans. This perhaps happened during a period when the plants had been neglected as a result of low product prices (Baker, 1990).

Subtropical, Highland Tropical and Arid Regions – Forestry and Orchards

Forest trees are attacked in this ecotype, although generally only passing reference is made in the review literature. Two groups can be distinguished: rodents causing similar damage to that in temperate regions by debarking, and those that cut down young plants. Differences in the composition of rodent communities infesting field and tree crops are less evident than in the temperate regions. Throughout most of the Asian region, the commonest 'specialist' tree damagers tend to be larger rodents, particularly the porcupines, *Hystrix indica* and *H. subcristatus*. They inhabit rocky or sandy country but make forays into woodland. Quite large trees can be ring barked, leading to their death. Squirrels cause damage to forest seedlings in Bangladesh. In India, large-scale plantations are grown for watershed management and forests are planted for timber and fuel. The growing points of trees are cut and their shapes restricted and disturbed by *Rattus cutchicus* and porcupines. The desert gerbil, *Meriones hurrianae*, can extend into arid land and affect reafforestation. For example, 20% of trees were lost in the Rajasthan Desert up to the end of the first year after planting (Barnett and Prakash, 1976). Young trees were completely cut down by *Nesokia indica*. In the forest plantations in the North Western Desert, debarking occurred on 3–4-year-old trees, and some were cut down (Tripathi *et al.*, 1992), mainly by *M. hurrianae*, *Tatera indica* and *R. meltada*, the principal rodents of the desert.

In Taiwan, squirrels, particularly *Callosciurus erythraeus*, cause serious debarking damage (Kuo and Ku, 1987). In Queensland, Australia, hoop pine plantations are severely damaged by *R. culmorum* (Kehl, personal communication).

There is a group of rodents that inhabit orchards. They climb the trees to feed on the fruits but do not primarily affect tree growth. In the Mediterranean region, field-adapted subspecies of *R. rattus* may do serious damage to fruit trees. In Cyprus, *R. r. frugivorus* debarks carob tree branches in the growing season from March to October. Attack is mainly on fresh branches, but may include older ones, causing dead patches in trees. Roughly up to 15% of trees lose 20% of their crop (Watson, 1951). The same species also damages citrus in Cyprus and other localities in the eastern Mediterranean, including the Nile basin. In the eastern Mediterranean, the edible dormouse, *Glis glis*, has a special niche as a consumer of olive fruits, causing an annual loss of 30 t in Iran alone (Greaves, 1987). It can also inflict serious damage in deciduous forest by debarking branches and destroying growing points.

In fruit projects in the North Western Desert of India, 29% of ripe pomegranates were eaten by *Funambulus pennanti*, which also takes other fruit such as grapes and guavas (Tripathi *et al.*, 1992). This squirrel is particularly notable in India, feeding on a range of fruits from flowering to maturity (Posamentier and van Elsen, 1984), up into the slopes of the Himalayas (Bhagat and Kaul, 1992).

Bamboo Forests in Tropical Mountainous Regions

This category has been added since the previous edition, because although it is a particular situation, it is extensive and it illustrates important features of rodent outbreaks into which more insight has been gained in recent years. This concerns the incidence of periodic but devastating outbreaks of rodents in crops grown in the vicinity of bamboo forest. These forests occupy vast tracts in tropical highlands, also extending into temperate climates, on all continents. They may be climax vegetation, or a recurrent stage in the succession that is maintained by slash and burn agriculture. The bamboos can have practical uses and some food value, while the crops grown seasonally in these localities provide food and cash crops for numerous towns and villages. Various rodents live in the environment, their populations limited by food availability, but periodic synchronized bamboo flowering and fruiting ('masting') provides a surge in nutrition that supports an explosion in rodent pest numbers. The reproductive biology of bamboo is varied (Aplin and Lalsiamliana, 2010) and ranges from species that flower individually and sporadically to those with synchronized masting, including 'semelparous' species that grow for long periods, then flower, fruit and die synchronously. The suddenly multiplying rodents spread into the croplands, causing destruction far beyond the usual levels of 5–15%, and leading to yields of only a fraction of normal or even to total loss. Historically, this has led to dramatic effects on the human population, as famine and starvation ensue (e.g. World Food Programme, 2009), as well as the diseases that such huge and uncontrollable rodent numbers can bring. Such events have occurred in various parts of India, Madagascar, Japan, Brazil, Chile and Argentina (Jaksic and Lima, 2003; Sage *et al.*, 2007).

Apart from the losses, there are important implications for rodent agroecology in general. One of the locations best known for these periodic rodent upsurges is the NE Indian state of Mizoram, which has over 9000 km^2 of bamboo forest. Among a range of bamboo species, *Melocanna baccifera* (locally called *mautak*) is predominant over 85% of the area. The dramatic consequences associated with its masting (called *mautam*) occur in a cycle of about 48 years, and were recorded in 1910–1912 and 1956–1959. Another species, *Bambusa tulda* (*rawthing*) may predominate, with synchronous masting and rodent upsurge at about similar (but out of phase) periodicity (*thingtam*), in 1880–1881, 1927–1929 and 1976–1978. While the earlier records inevitably are anecdotal, in view of the human population consequences, they are well documented.

Chauhan (2003) reviewed the subject and noted that, at that time, an opportunity to study a *mautam* in more detail would be expected in about 2006–2008. This did indeed take place, with widespread simultaneous fruiting moving progressively across the forest area from 2006 to 2008 (Aplin and Lalsiamliana, 2010). Huge amounts of fruit were produced, and rodent populations, which were clearly feeding on the fruit, built up vastly and dispersed widely into surrounding cropland, causing intense destruction. Crops were totally lost or reduced to a fraction of the usual expectation. Those affected included upland rice, maize, and lesser crops such as sugar, beans, oil crops, pulses, cassava, sorghum, etc., plus vegetables for local subsistence. This bamboo forest extends over wide territories with similar topography west to the Chittagong Hill Tracts of Bangladesh (Ahaduzzaman and Sarker, 2010), and south-east into Myanmar (Htwe *et al.*, 2010), and rodent outbreaks were recorded from 2007 to 2010. The extended time over which the bamboo masting events occurred, with areas flowering and fruiting at different times, was a surprise, and is the first time it has been so well documented at a regional scale (Singleton *et al.*, 2010a,b).

Control may be attempted, systematically and jointly, but there seems no realistic hope of preventing the extreme losses. Trapping and hunting may take huge numbers – figures of millions of bodies or tails (often in bounty schemes) are quoted in the literature cited here. Methods to scare rats away – patrols, noise, and so on, have no practical effect. Local poisoning projects do not prevent overwhelming survival of the pests, and it is doubtful if even area-wide systematic projects could make much difference at any economic cost. Protection by various barriers has not proved useful in face of the great pressure of rodent numbers, except for some possible help in storage facilities. Some farmers in the Chittagong Hill Tracts have developed an 'escape strategy' whereby they plant a shorter duration rice variety once they see the bamboo fruiting. This early-maturing variety, however, has a cost; the yields are generally 50% less than the late-maturing varieties. So farmers may escape high rodent losses to their rice but they have a considerably lower harvest (Belmain *et al.*, 2010). Fortunately, the consequent starvation in the human population was limited in the recent case study, because there is infrastructure to bring in essential supplies. Even so, this does not eliminate the longer term hardships to the farmers, which can extend to enforced consumption of seed that normally would be saved for subsequent planting seasons. In some regions, where the rodents form a regular or occasional part of the diet, there may be limited compensation.

Various rodent species are associated with these events. In Mizoram and surrounding territories, the commonest species recorded is *Rattus rattus*. This may well cover a complex of taxa, as there is a large range of body features. Other common rodent pests include *R. nitidus* (the Himalayan rat), *R. exulans* (the Polynesian or little house rat), and *Mus musculus* (the house mouse). Other species found include *Berylmys* spp. (white-toothed rat), *Niviventer fulvescens* (spiny rat), *R. sikimensis*, *Cannomys badius* (bamboo rat), *Mus* spp., *Chiropodomys gliroides* (bamboo mouse) and squirrels such as *Callosciurus* spp. (Aplin and Lalsiamliana, 2010). It is clear from the literature that by far the most serious pests are within the *R. rattus* complex, which generally make up somewhere around 80% of captured or killed batches. As the masting progresses, rodents will swarm over crop areas, sometimes appearing to return to harbourage, sometimes dispersing. Large numbers of 'mice' reported may actually be the young of the predominant rats, which increase to high proportions as the populations multiply rapidly (Aplin and Lalsiamliana, 2010).

Further east in the mountainous regions of northern Laos, there are extensive tracts of such forest, in which there is a greater range of bamboo species and more localization of dominance. Masting occurs in different places and with different periodicities, but crop loss by rodents can be extreme in some years and at some places (World Food Programme, 2009; Douangboupha *et al.*, 2010).

The link between bamboo masting and severe rodent upsurge is well established. Rat populations exist continuously in the bamboo forests, at populations regulated by the amount of food available. Areas of ripening crops only present a suitable habitat for rodents for short periods each year, so that opportunities for rapid population increase are limited. Various authors have noted the increase in 'breeding' or 'reproduction' at masting. It would no doubt be more precise to say 'an extension of the breeding season', plus increased recruitment opportunity. The massive increase in rodent food over an extended period leads to the explosion in rodent populations and, in turn, to the widespread dispersal of large numbers of rats – termed 'rat armies' in Mizoram (Aplin and Lalsiamliana 2010), 'rat floods' in the Chittagong Hill Tract region (Belmain *et al.*, 2010) and '*ratadas*' (both Spanish and Portuguese) in South America (Jaksic and Lima, 2003). Equally, as the extra food disappears, so do the excessive rat populations, themselves subject to starvation that often leaves many corpses in the landscape (Sage *et al.*, 2007).

Lowland Tropics

Lowland equatorial climates are hot, without distinct cool periods, and with plentiful rain for at least part of the year. Several commodity crops are grown on a large scale that are subject to heavy depredation by rodents. Detailed investigations have continued in recent years, with some important advances in ecological understanding and in the approaches to control. Each crop has particular characteristics, and they are considered individually here.

Rice

Importance in South-east Asia

This most important staple grain is grown throughout the tropics and as a summer crop in subtropical and warmer temperate climates (Maclean *et al.*, 2002). Rice agroecosystems are particularly conducive to rodent infestation; for example, rodents are categorized as the number one preharvest pest of rice in Java, Indonesia (Sudarmaji *et al.*, 2010), as among the top three pests in Vietnam (Huan *et al.*, 2010), and in the Philippines as the number one pest in dry season and number two pest in wet season rice (Palis *et al.*, 2008). Grassland rats are well adapted to rice, and damage can occur from nursery to harvest. Rice attack is probably the worst case of rat depredation in crops, threatening food security on a world basis, particularly in Asia (Meerburg *et al.*, 2009). Thus, sustainable measures to combat the pests are vital. In this context a 'source vegetation effect' of possible relevance in control was recognized from the 1970s (Lam, 1990; Wood, 1990). Intensified work towards more reliable and economic control by better understanding the population ecology has been a key feature since the mid-1990s. See Singleton *et al.* (2007) for a comprehensive review.

Rice may be grown by direct sowing, or by transplanting from a nursery. As an irrigated rice crop, it is grown in lowland paddies bordered by banks (locally called 'bunds'); it is also grown as rainfed rice in lowland and upland rainfed agroecosystems; there is also deepwater rice. Although there have been reports of rodent damage in Bangladesh (Islam *et al.*, 1993), not much is known about the impact of rodents in these systems. From early growth (tillering), stems proliferate (booting), the panicles form (heading) and ripen, in a growing season of from 3 to 5 months. Two crops a year are often grown in the lowland tropics, sometimes even three. Figure 3.2 shows the effect of rat damage at the booting stage.

Fig. 3.2. Rat damage to growing rice at the booting stage. The rodents have gnawed the bases of the growing tillers to obtain the developing panicles. Damage done at this stage may not be taken into account in damage assessments conducted close to harvesting because the remnant tissues will have rotted away. This leads to underestimation of the importance of rat damage to the rice crop, in this case by *Rattus argentiventer* in Malaysia.

Rodent species and occurrence

Many species are known to feed on rice in the field, but the worst, and certainly the most intensively studied, is *Rattus argentiventer* (the rice-field rat). It is the dominant species in the rice fields of Indonesia, Malaysia, Vietnam and the southern and central islands of the Philippines. Further north in the Malay Peninsula into Thailand, *R. losea* (the lesser rice-field rat) and *R. rattus* (a complex of taxa) become common, as does *Bandicota indica* (the large bandicoot rat). Eastward into Cambodia, *R. argentiventer* is common in the south, with *B. indica* and *R. exulans* (the Polynesian rat), but *R. rattus* becomes dominant in northern Cambodia and Laos. To the west into Myanmar and Bangladesh, *B. bengalensis*, *B. savilei* and *R. rattus* become the dominant species in rice fields. Aplin *et al.* (2003) provide a review of the biology and taxonomy of the main rodent pest species in agricultural landscapes in Asia and the Pacific.

Environmental suitability and causation of outbreaks

R. argentiventer naturally inhabits the environments suitable to rice cultivation, in particular with open vegetation cover and water courses, and makes incursions from these vegetation sources into rice fields. As the rice grows, it supplies nutrients that can support a rapid and abundant build-up of rat numbers. The population size towards tillering, the time of maximum susceptibility to crop loss, depends largely on the number of rats at the source at the time of planting, and their access to the rice. After harvest, when abundant food is no longer there, the high population may be sustained for a period in the straw and stubble of the crop (Brown *et al.*, 2006; Jacob *et al.*, 2010), but then declines to what is supported by the source until the next season. The population dynamics of other rice-field species have not generally been studied in such detail as those of *R. argentiventer*, but available evidence supports a similar build-up from source as more food appears – for example, *R. tanezumi* in Mindanao (Fall, 1977), *R. losea* in Vietnam's Red River Delta (Brown *et al.*, 2005) and *B. bengalensis* in India (Sridhara, 1992) – and it would be logical to assume that this generally applies.

Rat damage can be categorized as a continuous threat from season to season ('chronic') or as episodic and resulting from occasional population eruptions ('outbreaks'). The chronic situation is described above for *R. argentiventer*, which rises regularly from populations in source vegetation. Outbreaks are of two main types. One is the irregular appearance of a big surge in food other than rice. The prime case is in the areas where bamboo masting (q.v.) takes place. The species that build up will attack and probably destroy any rice that they find (mainly rainfed in such cases) (Schiller *et al.*, 1999; Singleton *et al.*, 2010a,b).

The second cause of outbreaks is when for any reason the rice planting programme within a restricted locality is asynchronous. Such practices may be started when there has been disruption to earlier planted crops, as can happen from unusual or extreme climate events, in particular heavy rains or a delay in the onset of the monsoon rains. Further, paddies may be left uncultivated after the harvest, and so a continuous large rat population is sustained by the subsequent volunteer crop. Freshly cut rice tillers at harvest can quickly regrow if there is sufficient water available, leading to a 'volunteer' or ratoon crop. Such incidences are documented for the Philippines and Indonesia (Singleton *et al.*, 2010a,b; Sudarmaji *et al.*, 2010), and for Vietnam (Huan *et al.*, 2010). When cyclone Nargis struck the Ayeyarwaddy area in 2008, it wiped out extensive rice-field tracts. Attempts to make this good led to disrupted planting schedules which, in turn, extended the breeding season of *Bandicota* spp. (Htwe *et al.*, 2013). There was consequent heavy loss of the crop. The pressure is high on smallholdings (most farmers in South-east Asia have less than 2 ha of land) to maximize land productivity. This means planting the crop as early as possible so that the smallholders can generate income and/or plant a third crop. Moreover, some of the newer varieties of rice have markedly shorter growing seasons, leading to the temptation to have interspersed plantings of different periods. Thus, with contiguous smallholdings, there can be a high degree of asynchrony, a likely cause of rodent problems.

Review of crop losses

Rat damage is very clearly severe at many times and in many places, but is not easy to quantify on an ongoing basis. A key reason is that while the main loss is caused during the growing phases, vegetative recovery can disguise the appearance of damage at harvesting. This, though, is when much of the assessment tends to be done. Further, some of the production on recovered stems is too late for the harvest, and early vegetative damage may reduce the canopy and so allow increased weed competition (Wood and Chung, 2003).

Nationally, loss estimates may depend on farmer surveys and subjective assessments – often on a basis of what crop is taken without any same-time reference point to what it could have been. Such guides may be useful but can be wildly inaccurate, and patchy incidence can further blur the picture (Barnett, 2001). Even so, there is sometimes a spurious impression of precision because a collection of estimates is averaged to a non-rounded figure. Often, the subjective assessments seriously underestimate true losses. Nonetheless, broad regional assessments suggest large losses in all Asian countries and, importantly, very heavy loss, even loss of the complete crop, is an ever-present threat. Nationally, this may not have a big impact, but for individuals and in districts it can seriously reduce income, production continuity and even adequate food availability (Leung *et al.*, 1999; Aplin and Lalsiamliana, 2010). In Indonesia, for example, 50% loss can be common for an individual farmer; e.g. in 1995, some 5225 ha were totally lost (Singleton, 2003). In the uplands of Laos, occasional population eruptions can place a major strain on the food security of families (World Food Programme, 2009).

In Indonesia, irrigated rice yields have recently been high, which is attributed to improved agronomic techniques and the use of high-yielding varieties. Yields averaged 4.40 t ha^{-1} in 2000, progressing to 4.94 in 2009. Even so, rat damage is a constant drag on yield, with an average 3.5% perceptibly damaged at harvest (damage has to equate to at least 10% crop loss before it is noticeable) and 0.02% wipeout. Some years and places can be worse, such as West Java in 2008, where over 9% of the crop was recorded as damaged, with yield down to 1–2 t ha^{-1} in some trials without rat control (Sudarmaji *et al.*, 2010). For other countries in South-east Asia, Singleton (2003) tabulated losses in various territories, including: Laos <5% in lowland rice, 10–15% in upland rice and more in outbreak years; Myanmar, 5–40% plus outbreaks; Philippines variable, with district losses of >20%; and Thailand, 6 or 7%. Further figures include 20–30% losses in Vietnam (Brown *et al.*, 2005), and here there is a worsening situation as rice planting is intensified.

Another source of crop shortfall is foregone planting, which can occur as a result of rat damage (Singleton, 2003). In Indonesia in 1998, a drought disrupted production. A third crop was planned by the national government to be planted in an attempt to compensate for the lost production, but because it was recognizably subject to a heavy rat threat, the area planted to a third crop was considerably less than intended. A planned expansion of the rice area in Kalimantan (Indonesian Borneo) to 900,000 ha was abandoned half way through because of attack by rats, and other farmers in the territory have given up growing rice.

Relationship of damage to production

The relationship of damage to crop loss has been determined objectively in some trials. Fulk and Akhtar (1981) used a statistical method to hold tiller density (the main non-rodent factor affecting yield) constant, and showed a direct relationship between yield and rodent damage counts made at harvest. Using the method in Malaysia, wide damage estimates were reached, from 2 to 10% in individual fields (Buckle *et al.*, 1985) to 12–47% in blocks without rat control (Lam *et al.*, 1990). In Indonesia, the percentage of tillers cut by rodents in the 2 weeks before harvest would need to be multiplied by three (Buckle, 1988) or by four (Singleton *et al.*, 2005) to provide an estimate of percentage crop loss. A replicated trial in the Mekong Delta in Vietnam (Cuong *et al.*, 2003) compared the effect of rats put into 3 × 3 m enclosures, using two, three or four animals for two nights at three crop stages. Tillers damaged at the seedling stage were respectively 25% (two rats), 38% (three rats) and 62% (four rats). Damage at tillering was 21, 27 and 43%, and at booting was 20, 25 and 27%. This seems to suggest that damage lessens as the rice grows; however, the yield loss against control values (enclosure with no rats) was 0% at the seedling stage for all rat numbers, but 42, 43 and 53% down at tillering and 52, 59 and 62% at booting (early stage of seed development).

Objective assessment of loss

Loss assessment can best be done by comparing yield with and without rat damage (Chapter 10). In the Malaysian Peninsula in the 1960/1970s, an effective way to eliminate rats was developed, with attractive anticoagulant baits on a replacement round system. A series of ten paired comparisons was done, at the field scale (single plots of 10–50 ha), on different rice-growing areas of varying yield potential (Liau and Wood, 1978; Wood, 1984a). Yields without this control (but with 'usual farmer practice', if any) ranged from 1.4 to 4.8 t ha^{-1}, with an arithmetic mean of 2.5 t ha^{-1}, which, as it happened, was close to the national average at that time. In the baited areas, the yields were from 2.3 to 6.2 t ha^{-1}, mean 4.4 t ha^{-1}. All of the dead rats found were *R. argentiventer*. One test area was in a large 'rice bowl' that ranged from intensive rice planting only, with narrow bunds and no residences, in the north, progressively changing to a more mixed system with houses and gardens among the paddies, and broader access bunds ('non-rice land'), in the south. In plots respectively in the north, middle and south of this, untreated yields were 4.8, 4.0 and 2.5 t ha^{-1}, but with rat control, they were 4.9, 4.7 and 4.9 t ha^{-1}. As well as revealing the losses to rats, not always obvious nor appreciated by farmers, this showed the variability of rat incidence, which could clearly be linked to the extent of 'non-rice land' (a rat source). This margin of difference was confirmed by others, e.g. Ding (1975). Buckle (1988) found increased yields of 4.4 and 3.7 t ha^{-1} in two seasons with second-generation anticoagulant baits, against 3.0 and 2.4 without them. Inside fenced plots, Lam (1990) obtained yields of 4.2 and 4.4 t ha^{-1} in two localities, against 1.1 and 0.8 t ha^{-1} outside fences.

An interesting speculation relates to rice yields after the tsunami of 2004 in the north of Sumatra. The first rice crop afterwards produced 4.2 t ha^{-1}, against the usual local expectation of about 2.6 t ha^{-1}. Severe and widespread flooding would severely reduce rodent densities, and the yield difference ('Tsunami bonus') appears to accord with the above differences demonstrated with and without rodent control (Wood, 2006).

Rat population size

The numbers of *R. argentiventer* present are hard to quantify objectively. Many authors note that individuals are difficult to trap, and even more so to re-trap (e.g. Leung *et al.*, 1999; Jacob *et al.*, 2003). This makes conventional ecological techniques, with catch–mark–release/recapture (CMR) methods, very imprecise (Singleton *et al.*, 1999b). Wood (1971), after a period of CMR, took the index capture by hunting rats alarmed by the plough. This indicated 60 rats ha^{-1} at the end of the growing season. An alternative index collection can be the corpses from a round of poison baiting after a trapping period. Indirect methods of estimating the number of live rats present include activity signs such as the number of active burrows. In Indonesia, the population during the growing season was estimated at 5–25 ha^{-1}, rising to over 700 ha^{-1} at 1–2 months after the harvest. The associated population in a source habitat can be very dense; in the Philippines, one estimate was 10,000 ha^{-1} (Fall, 1977). Sometimes, the number taken in attempts at control by killing rats gives an impression of the scale of the problem – for example in West Java in one season in 2001, rats removed from two 100 ha blocks were, respectively, 8729 and 5429 (Singleton *et al.*, 2005). More recently, in Indonesia, the numbers of rats in burrows and straw piles after harvest were estimated at 120–140 ha^{-1}, and the actual numbers caught in large areas in four districts were from 34 to 222 ha^{-1} (total of 163,645 from 1787 ha) (Leung *et al.*, 1999). In the Mekong Delta, in a bounty scheme over 22 provinces in 1997, 55 million rats were collected (Singleton, 2003).

Ecological basis of control

In attempts at culling, whether by physical or baiting means, in a patchwork ownership by small farmers, control measures require collaborative coordinated effort. Unfortunately, it is too often delayed until damage becomes obvious (Stenseth *et al.*, 2003), which includes late intervention by bodies of authority (Huan *et al.*, 2010). By this time, the main loss has already occurred and the rat population is too widely distributed in the agricultural landscape for effective removal (Brown and Tuan, 2005).

The good results from anticoagulant baiting (mentioned above as demonstrating losses) are rarely adopted by farmers in the field. Negative factors include: farmer preference for acute poisons so that they can see dead rats (although bait shyness means that they rarely reduce populations to low numbers); various payment and subsidy issues; competition from commercial manufacturers who produce baits for multiple use that are less effective in rice fields; and the poisoning of non-target animals. Resistance and other sustainability issues arise in the long term.

EBRM has been particularly developed in rice. The basic aim is to reduce the threat from source habitats, and then to apply acceptable and sustainable measures against the post-planting increase. The key components vary according to the specific location, but they generally include: reduce suitable source habitats (sanitation, neutralizing burrows, remove excessive ground vegetation, reduce bund size as appropriate); ensure neighbouring crops are synchronized; community actions to remove rodents during the 2 weeks after transplanting (or 4 weeks after seeding). The last is timed when rats are aggregated in source habitats around the margins of rice fields, and before the main breeding season commences. A coordinated community effort ensures the best chance of success.

Where rodent losses are typically >10%, as in the dry season in West Java, an additional element to EBRM is the use of the trap-barrier system (TBS). Rats are guided to multiple-capture traps along a low fence line. This can take huge numbers of rats, e.g. about 44,000 in 200 traps along an 8 km boundary (Lam, 1990; Lam and Mooi, 1994). A ‘second generation TBS’ lures rats to a ‘trap crop’ planted 2–3 weeks ahead of the main crop (Singleton *et al.*, 2003b). Rats are attracted to the earlier planted crop, and are taken in multiple-capture traps. The TBS with a trap crop gives a halo of protection of about 200 m (Brown *et al.*, 2003). In the development trials, three sizes of trap crop plots were compared with two replicates. The highest catch was with the biggest plot (50 × 50 m) with a total of captured rats at tillering, booting and ripening stages of 1584 rats, against 484 in 30 × 30 m plots, and 567 at 20 × 20 m. All plot sizes gave a similar yield improvement, averaging 4.72 t ha^{-1} as against 4.10 t ha^{-1} without the TBS.

In one project, farmers generally agreed that rats were damaging but varied in their attitudes to the value of cooperation (Sudarmaji *et al.*, 2003), whereas farmer involvement is crucial to success (Morin *et al.*, 2003; Palis *et al.*, 2011). As an example, EBRM with strong community involvement (community trap-barrier system, or CTBS) was tested in West Java from 1999 to 2002. Yields in four villages, each with about 120 ha, were compared. Two were assigned to EBRM with CTBS, while in the other two, farmers made their own decisions (Singleton *et al.*, 2005; Jacob *et al.*, 2010). The treatment villages took steps to reduce source populations, with eight 20 × 20 m trap crops for about 2 weeks around planting. Yield assessed from a similar quadrat pattern of transects in each village showed a consistent advantage over the 11 seasons of from 110 to 890 kg ha^{-1}, on total yields of 5.4 to 8.6 t ha^{-1}. Culling needs to be intensive and systematic. In one season, catches from 100 ha were 8729 and 5429, respectively, from the treated villages. In later developments in West Java, yields in the Indonesian Center for Rice Research improved from 3.4 t ha^{-1} before 1998 to 7–8 t ha^{-1} from 2006 when TBS was practised (Sudarmaji *et al.*, 2010). In a parallel trial in the Red River Delta of Vietnam, there was no yield benefit, although the use of rodenticides did decline. This was attributed to low rat populations during the trial period (Singleton *et al.*, 2004; Brown *et al.*, 2005). In another scheme, in the Mekong Delta, there was a reduction of rat damage from 16 to 1%, with a corresponding yield increase (as acknowledged by the farmers). In the Philippines, in 2006, strong liaison with farmers, and intensive publicity, enabled a coordinated scheme; from farmers' own assessments, yield improvement was judged to be over 10% (Flor and Singleton, 2010).

The TBS is expensive to set up, and there needs to be evidence of a probable significant rat attack. Generally, the dry season is when the danger is greatest, hence is the most cost-effective time. Thus, a good prediction system is desirable (Huan *et al.*, 2010). Much of the area in the Vietnam irrigated rice areas is subject to heavy flooding in the wet season which 'resets' the rat population.

Other regions

Moving from South-east Asia, rice is also heavily attacked by rats in the Indian subcontinent. Across to the west in Pakistan, *B. bengalensis* is the major rice rat. It too cuts tillers, but losses are compounded by its habit of storing food in its burrows. Rat damage has been a principal reason why the planting of rice has not increased in some regions (Greaves *et al.*, 1977; Fulk and Akhtar, 1981). Other common rice-field species are *Nesokia indica*, *Millardia meltada* and *Mus* spp., which appear to eat grain but do not cut down stems. *B. bengalensis* responds to the growth of rice by increasing its population (Smiet *et al.*, 1980), like *R. argentiventer*, but *M. meltada* does not show this response. Investigation in fields not considered especially heavily infested showed a mean population of 55 rats ha^{-1}, 60% of them *B. bengalensis*. Damage to tillers ranged from 10 to 25% with a yield loss of 2–43% (mean 19%) (Fulk and Akhtar, 1981). Elsewhere, the application of rat-control measures gave a mean yield increase of 21.4% (with only 3.4% of evident tiller damage) (Greaves *et al.*, 1977).

To the east, in Bangladesh, the principal rice pests are *B. bengalensis* and *B. indica*. Economic assessment of loss is limited, but reached 68% in 1987 and 32% the next year (Islam *et al.*, 1993). In 1982–1983, counts of stems cut in deepwater rice led to estimates of 0.9% loss (Karim *et al.*, 1987), but excavation of burrows indicated much bigger losses. There are also acute, sporadic losses associated with the 'rat floods' associated with bamboo masting (q.v.) (Belmain *et al.*, 2010). In 2007–2008, rodent outbreaks in the Chittagong Hill Tract region led to significant reductions in the livelihoods of families and increased health issues (Ahaduzzaman and Sarker, 2010).

In India, *B. bengalensis* is the major rice rat, with *M. meltada* and the mouse *Mus booduga* common as well. *B. bengalensis* increases as the rice matures. Two or three decades ago, rodents were reported to consume 10–15% of all grains (Barnett and Prakash, 1976). Various Indian states estimate, for rice grown with all watering methods, chronic loss in the 2–3 to 15%

range, and with frequent cases of much higher damage (Singleton, 2003). Some of these rodent outbreaks, and consequent heavy losses, have been associated with bamboo masting (q.v.) in NE India from at least the 1980s (Sridhara, 1992).

In China, rats have long been a problem in rice, but detailed evaluations have not been available. In the period before 1985, the official estimated loss was 10% (Zhao, 1996). The main species are *R. norvegicus*, *R. losea*, *R. tanezumi* (= *R. flavipectus*), *R. nitidus*, *B. indica* and the mice *M. musculus* and *Apodemus agrarius*. Other species may also occur as pests. In the Pearl River Delta, the main pest appears to be *R. rattoides*, which makes incursions into growing rice from other vegetation, including other field crops. One of the ways of reducing the source is to grow trees that shade out the preferred low vegetation habitat (Zhang *et al*., 1999). In Taiwan, *Bandicota nemorivaga*, *R. losea* and *M. formosanus* are common and will attack rice.

Reports on rat damage to rice in Africa are fewer than from Asia, but serious losses clearly occur. Among several small rodent species in rice fields in south-west Nigeria, tiller cutting was mainly by *A. niloticus* or, in flooded fields, by the shaggy rat, *Dasymys incomtus* (Funmilayo and Akande, 1977). *Tatera kempii* also cuts stems, while several species remove seeds, primarily *Mastomys natalensis*, *Lemniscomys striatus*, *Uranomys foxi*, *R. rattus* and *Mus musculoides*. Some species attack nursery plants, including *X. erythropus*. In general, rice is not seriously attacked by hystricomorphs, but in West Africa the grass-cutter, *T. swinderianus*, can cut down about 5% of individual plots. Overall, by comparing places with and without damage, losses to vertebrates were estimated at 40%. In East Africa, in Tanzania, *M. natalensis* is the main rodent pest of lowland irrigated rice (Mulungu *et al*., 2013); however, estimates of losses to rice caused by rodents are lacking.

Again, based on rather sparse reports, a similar situation appears to prevail in South America. Losses were estimated roughly at 15% in two studies (Williams and Pereira, 1984; Williams and Vega, 1984). In one locality, 85% of rats captured were *Holochilus brasiliensis* and 13% *Sigmodon hispidus* (or *S. alstoni*), and in another, 27% and 73%, respectively. Rice grown in areas affected by population explosions ('ratadas') associated with bamboo masting (q.v.) is subject to heavy or total loss, like many other crops (Jaksic and Lima, 2003).

In more seasonal climates, where rice is grown as a summer crop, it is attacked in much the same way as in the tropics by species similar to those affecting field crops in the area, such as *Arvicanthis niloticus* and *R. rattus* in Egypt.

Sugarcane

Sugarcane is widespread, growing best in the zone bordering the tropics and subtropics. It requires good rainfall most of the time, but with a dry season for full ripening. Planting is possible at any time. The canopy remains open for about 6 months, then progressively closes over. After about 12 months, the cane starts to lodge and a mat of stalks and leaves covers the ground. This provides ideal food and shelter for small rodents, and is stable in the medium term, until the cane is harvested, after a period that varies widely – from 1 to 3 years in different regions. Rats cause direct loss of cane by eating into the internodes of standing and lodged cane. This permits entry of insects and pathogens, and also causes physiological stress, which reduces the weight and sugar content, and may kill the cane. Damage may also come from the eating of growing tissues, and of underground parts by fossorial species. Loss relates to the proportion of damaged canes, but quantification is complicated by the time from harvest and other factors. Various ways to estimate losses have been devised (Chapter 10). Damaged cane that does not die loses around 10–20% of its sugar content. The proportion of damaged canes is often high, up to 90% or more, with a significant proportion dying. In examining a range of findings from various countries, Hampson (1984) found a constant ratio between the proportion of canes damaged and lost sugar yield.

Yield potential varies widely, in the range 2–6 t ha^{-1} sugar, but for each 10% damaged, the sugar loss is about 3–4% (mean 3.7%).

In the Americas, *Rattus exulans*, *R. norvegicus* and *R. rattus* all occur in cane fields in Hawaii, the first species being the commonest and most damaging. Populations are maintained in unplanted areas of natural vegetation, such as gulches. Breeding can take place all year round and the rats spread into the cane fields as conditions become suitable (from about the fourth month). Numbers are estimated conservatively to reach 30 ha^{-1} (Hood *et al.*, 1970). In the 1960s, losses were estimated at 40% cane damaged, with 30% of this dead. *Holochilus sciureus* occurs through the north of South America, and is particularly noted in Guyana (Bates, 1963). It breeds all year round in vegetation surrounding the fields and spreads into young sugar fields. Losses of sugar are estimated at about 12%. In Central America, *Sigmodon hispidus* is the commonest sugarcane rat, along with *Oryzomys palustris*, *R. rattus* and *M. musculus* (Romero *et al.*, 1978). The population was estimated at 39 ha^{-1} and damage to cane was in the range 2–43%. In Mexico, attacks by *S. hispidus* start when canes are 12 cm high and worsen as cane is toppled, with the rice rat, *Oryzomes coues*, and deer mice, *Peromyscus* spp., also recorded; occasionally 90% of canes can be damaged (Collado and Ruano, 1963). In Florida, *S. hispidus*, *R. rattus* and the round-tailed muskrat, *Neofiber alleni*, caused damage averaging 14% over 41 fields, with a calculated yield loss 10.8% (Lefebvre *et al.*, 1978). In Barbados, introduced rat species can cause extensive losses, up to 6% in some years (Taylor, 1972).

In north Queensland, cane is attacked by the grassland rat species *R. sordidus* and *Melomys burtoni* (Smith *et al.*, 2003). The rats build up from source populations in the fallow and surrounding vegetation, and the cane provides suitable food and ground cover for the burrowing of *R. sordidus*. Some degree of control is achieved by removing the supporting vegetation. The risks of broadcasting second-generation anticoagulants led to the suspension of this control method; in any case, baiting is generally done too late when damage is already apparent. Limited input of an improved formulation zinc phosphide (which rapidly degrades in the field) gives good control based on the ecology. *R. conatus* and *Melomys littoralis* are also recorded as sugar pests, with marked annual variation in losses (Armstrong, 1984).

In the Indian subcontinent, sugarcane is an important crop subject to heavy rodent damage. The commonest culprit is *B. bengalensis*, which has caused damage as high as 63% of canes in Andhra Pradesh (Mohan Rao, 2003). In Punjab, *R. meltada* is common, and there are some species particular to certain regions, e.g. *Cannomys badius* in Nizoram. The degree of infestation is related to the suitability of surrounding vegetation to maintain populations, which includes, in the case of *Nesokia indica*, the range of other crops that it attacks. Other lesser problems in India are from squirrels and porcupines (Srivastava, 1992). In Pakistan, the cane crop has an annual cycle (Smiet *et al.*, 1980). *M. meltada* breeds all year maintaining a relatively constant population. *B. bengalensis* increases markedly in mid-year, as the sugar grows up. *B. indica* attacks sugar in Bangladesh and *N. indica* feeds on the subterranean parts of plants, causing them to die without obvious symptoms (Posamentier and van Elsen, 1984).

R. losea and *B. bengalensis* are serious threats to sugarcane in China, and in Taiwan, *Mus formosanus* and *Apodemus agrarius* are abundant in the crop. In Egypt, *R. r. frugivorus* spreads into the fields when the canopy is dense, and *Arvicanthis niloticus*, a burrowing species, invades from the periphery. Damage can reach 40% of canes, with some cut down completely (Tantawy Omar, 1984).

Sugar is not a major crop in Peninsular Malaysia but, in pilot projects, an estimated 40% of canes were damaged, with *R. exulans* the commonest species (Wood, 1984a).

Oil palm

Rat damage was noted on oil palm fruits in Malaysia as early as the 1930s, when the industry there was in its infancy. Detailed investigations began in the late 1960s and paralleled the increasing importance of the crop, which occupies around 4–5 million ha in the country, and about the same in Indonesia, with extensive plantings in surrounding territories and other wet tropical regions of the world. Field plantings have a life of 20–30 years, with an immature period (open canopy and little or no fruit production) of about 2–3 years. Palms produce bunches at the base of the crown, each carrying a large number of tightly packed fruitlets with a kernel, shell and the palm oil-bearing mesocarp. Rats gnaw the unripe bunches, even through to the kernels, leaving characteristic scarring, which can be distinguished as 'fresh' (for 2 or 3 days) (see Fig. 3.3) or 'old'. Ripe fruitlets detach from the bunch and rats also feed on those and often carry them away.

Detailed ecological studies of rat population dynamics, and control measures based on the studies, have been reported (Wood, 1984b; Wood and Liau, 1984a,b; Wood and Chung, 2003). In the 1960s and 1970s, *Rattus tiomanicus* was the only rat captured in oil palms in the Malaysian Peninsula. Estimates by CMR techniques indicated that populations varied from 160 to 507 ha^{-1} (average about 300) at ten locations. *R. tiomanicus* inflicts similar damage on palms grown in surrounding territories in the region.

The rats feed on the oil-bearing tissue, which comprises only a relatively small proportion of the total harvested weight of the crop, making yield differences based on the weights of harvested bunches too insensitive for loss estimates. Instead, estimates of potential yield loss can be derived from the known size of rat populations found in oil palm plantations, average crop yields and the amount of fruit consumed by captive animals (which take it as bulk diet, although needing a small protein supplement to survive). Estimates derived in this way have indicated losses of about 5% of the average oil yield. This does not include detached fruitlets carried away by rats but not eaten, which increases the estimate to as much as 10% (Liau, 1990).

An *R. tiomanicus* population in a 100 ha block left without control fluctuated gradually between 200 and 600 ha^{-1}, with three

Fig. 3.3. Fresh rat damage to an oil palm fruit bunch in South Sumatra. Oil palm is susceptible to attack by many rodent species. High rat populations may build up as palm stands mature and produce fruit, in particular infestations by *Rattus tiomanicus* in South-east Asian plantations. Photo credit: Adi Sumantri.

troughs and two peaks, over a period of about 20 years. In a neighbouring plot, there was near elimination of rats by a technique of replacement round baiting to full uptake. Recovery of numbers followed a sigmoid curve, with <10 ha^{-1} for about 6 months, increasing rapidly from 6 to 18 months, and then gradually levelling off to the same number as in those plots without control (Wood and Liau, 1984a). Various other rat species predominate in the vegetation types adjacent to oil palm estates, but among over 46,000 records of *R. tiomanicus* captured in the palms, only a few individuals of other species were taken, all just after a control campaign (viz. *R. exulans*, 12; and two forest species, *R. rajah*, five, and *R. whiteheadi*, ten).

Among other species in oil palms in the region, the rice-field rat, *R. argentiventer*, may occur in younger palms. This is a fossorial species (unlike *R. tiomanicus*), and its distribution may be restricted by the suitability of soils for burrowing. Thus, particular young plantings are affected, and although numbers seem to be in the same order as for *R. tiomanicus*, damage is more conspicuous. *R. argentiventer* is evidently less adept at climbing and is replaced as palms approach 5 years old, when the fruit bunches are at about 1 m height.

R. rattus diardii was known as a commensal pest in Malaysia, only seen in the field near human habitations (Medway, 1978), but from the late 1980s, it began to appear in oil palms in some localities. By chance, one early appearance was in an ongoing study block without rat control, where it replaced *R. tiomanicus* over a period of 2–3 years (Wood and Chung, 1990). Various reasons were adduced (see Synthesis).

In 1969, a Far Eastern strain of the barn owl, *Tyto alba javanica*, was found in a Malaysian oil palm estate (Duckett, 2008). Early work showed that it could be established in plantations by the provision of nest boxes, and would eat rats and multiply. Theory does not well support the likelihood that a predator such as this would reach an equilibrium position in which it could keep its prey continually at a lower (and economic) number than it would otherwise be at (Wood, 1985; Lim *et al.*, 1993; Singleton *et al.*, 2003c). Nonetheless, since the 1970s, owl establishment has become an accepted practice in the region (Duckett, 2011). Visible rat damage is regularly reported to be low where owls are established, with nesting boxes provided at around one per 10–15 ha. There has been little objective comparison of actual rat numbers with and without owls, nor any comparison with simply stopping rat control. Conversely, there have been suggestions that rats became more serious after commencing systematic rat control by baiting, with the implication that some ecological balance factor was disrupted, with prolonged effect (Wood and Chung, 2003). The high population in trial plots comparing ‘no control measures’ did not support this, but possibly even plots up to 100 ha are too small for any change in equilibrium. The percentage of palms with fresh damage gives some indication of rat incidence, but it is affected by a number of other variables.

Chung *et al.* (1995) did find some reduction in rat numbers after 21 months with barn owls and without baiting, but the numbers were not as low as in the baited comparison, and there was no comparison without any active measures. Current observations in this respect are interesting. In North Sumatra, *R. tiomanicus* was active in the 1970s, much as in the Malaysian Peninsula (Wood, 1974). Later, infestation caused concern and some estates established barn owls from 1992 (Heru *et al.*, 2000). They found that damage declined, and is still not causing concern. However, several other estates with no signs of barn owls also have little rat damage. No baiting or other control has been done for some years, and is not at present considered to be necessary. The preliminary assessment is that rat populations now are generally low in the region, which has extensive mature palm areas.

In South Sumatra, where oil palm planting has expanded in the last two decades, rat damage is more evident, and baiting is commonly practised, under various protocols (Sumantri and Wood, 2012). The ecological factors behind these regional differences are being investigated, including ground vegetation and the volume of detached fruitlets left on site. Possibly, populations regulate at lower numbers after a period of no action (Wood, B.J., Sumantri, A. and Cahyasiwi, L., unpublished). Duckett (2008) notes that, in general, there is a build-up of endemic predators after a period with no other control measures following the establishment of a barn owl population. This may be a key factor but, in light of the reservation about the possibility of an equilibration of rats to lower numbers that would be likely to result from the presence of large predators such as owls (see above), it seems possible that other biotic factors may be involved. The approach to optimizing rat control by further investigation of their ecology fits in well with the concept of EBRM, and the ecological techniques that have developed over the years to monitor populations should ensure good objectivity in these comparisons.

Young palms may be gnawed at the base by rats before they begin to fruit. The pests occasionally penetrate the bud and kill the palm. Hystricomorphs are conspicuous pests at this stage. In the Far East, the Malayan porcupine, *Hystrix brachyurus*, can destroy large numbers of palms, though this is usually confined to the locality near its habitat in secondary jungle or scrub. Among sciuromorphs, the red-bellied squirrel, *Callosciurus notatus*, is common and feeds on palm fruit. However, population densities do not seem to rise sufficiently for it to be a serious fruit pest. On one occasion, young palms in a replanting were heavily attacked by squirrels (Wood *et al.*, 1970), but this has not become a common occurrence despite the extensive replanting that is done after the felling of old palms that do support a squirrel population.

The oil palm originated in Africa and it is grown commercially both there and in South America, as well as in the Far East. In Africa, heavy rodent damage to fruit can occur (Greaves, 1964), but is much less regular than in Peninsular Malaysia. Young palms are subject to damage by many species (Delany and Happold, 1979), and rodents are actual or potential threats in most agricultural situations, often of underrated consequence until objective studies are done (e.g. up to 80% losses were recorded in Nigeria in a year). Common rodent species in Nigeria and Ivory Coast are *Dasymys incomtus* and *Lophuromys sikapusi* and, in addition, in Nigeria, *Tatera valida*, *Oenomys hypoxanthus*, *Praomys morio* and *Mus minutoides. Lemniscomys striatus* and, the most important, *Uranomys ruddi*, occur in Ivory Coast (Bellier, 1965). The hystricomorph, *T. swinderianus*, can be quite damaging to young palms. No reports were found of significant rodent damage to oil palms in South America.

Coconuts

Coconuts are grown in villages and organized plantings. They are important to the economics of many tropical islands, and some important general advances in field rat control originated in coconuts (Smith, 1967).

Rats climb palms of all ages, and the developing nuts they feed on then fall prematurely. Assessment of actual losses is not straightforward, because natural ‘thinning out’ takes place, and compensation by increased weight of the remaining nuts is possible. In Pacific islands, the palms are attacked by introduced rat species, which appear to have displaced native species such as *Rattus praetor* in cultivated areas (Hitchmough, 1985). *R. exulans* was probably a very early introduction by man. *R. rattus* is the predominant cause of damage but, where it is absent, *R. exulans* causes equally severe damage (Wodzicki, 1972). Damage is often very high, typically up to 50% (Wilson, 1969). Williams (1971) noted losses of 38% in Fiji, 5–71% in Jamaica and 16–77% in the Gilbert and Ellice Islands, but suggested that the actual loss of copra was much smaller due to compensatory factors. In the Tokelau chain of islands in the Pacific, a comparison of islands with and without rat damage shows a much bigger nut fall in the former, and Wodzicki (1972) concluded that yield potentials were almost halved by rats.

In India, Keshava Bhat (1992b) showed losses varying between states from 8.7% in Andhra Pradesh to 50% in the Lakshadweep Islands. The main species include various subspecies of *Rattus*, in particular *R. r. wroughtoni* and *R. r. rufescens* in mainland India, and *R. r. andamanensis* and *R. r. holechu* in the Andamans. Squirrels commonly inhabit palms and evidently feed on the nuts, but reference to their economic effects is scarce. Nursery and young field palms may also be attacked by the ground-dwelling rodents *B. bengalensis*, *B. indica* and *Tatera indica*. The porcupine *Hystrix indica* also attacks at this stage.

Cocoa

Cocoa (cacao) is an important export crop in many tropical regions. Rodents bore into the pods, and larger bodied species can take whole beans, while small ones may feed only on the mucilage that surrounds the beans. The proportion of holed pods can be very high, and they become increasingly susceptible to damage as they ripen. The damage is compounded by ensuing fungal infection and affected pods are all lost. Reports of systematic investigations are few but, clearly, the amount of damage is very variable and depends upon the conditions under which the cocoa is grown. Cocoa pods alone appear not to provide a complete diet for rodents (Williams, 1973). The position is affected, therefore, by whether the cocoa is grown in monoculture (including under shade trees that do not provide rodent food), or is grown in mixed culture with a plant that does provide rodent food (in particular, coconut as shade).

Cocoa grown under coconuts is susceptible to attack by both rats and squirrels. In the Pacific islands, up to 60% of pods may be lost (Williams, 1973). In the Far East, palm rats and squirrels, in particular *Callosciurus notatus*, can cause damage. The latter may cause severe bark stripping of young cocoa plants (Hafidzi, 1982). Pod losses vary widely, but reach 90% at times (Han and Bose, 1980; Wood, 1984a). Otherwise, persistent widespread damage is only likely near to borders with crops that support rats, e.g. oil palms or rice, where losses may reach 100%. Heavy losses can occur in India, e.g. from the Western Ghats squirrel, *Funambulus tristriatus*, the south Indian palm squirrel (*F. palmarum*) and *Rattus wroughtoni* (Keshava Bhat, 1992a; Baco *et al.*, 2010).

Rat damage is common in West Africa, although apparently not generally at very high intensity. For example, in one study a loss of 6.8–14.6% (mean 8.2%) was recorded (Everard, 1964). A range of species was trapped, the commonest being *Hylomyscus stella* and *Praomys tullbergi.* Other species involved in damaging cocoa in West Africa include *Stochomys longicaudatus*, *S. defua* and *Praomys morio*, which, among local ground-dwelling rodents, appear to have good climbing ability. Squirrels (e.g. *Funisciurus anerythrus* in Nigeria and *Paraxerus poensis* in Ghana) may also be found (Delany and Happold, 1979), ranging into cocoa from other habitats. Smith and Nott (1988) recorded losses of a ripe cacao crop caused by squirrels exceeding 40% in the island part of Equatorial Guinea.

Other territories where rodent damage to cocoa is recorded include the West Indies, Pacific islands and South America. Losses appear to be in the same broad categories as those mentioned above (Taylor, 1972).

Other tropical crops

Rodents cause damage to other crops in the wet lowland tropics. Both commodity and subsistence field crops may be attacked by species that live in open conditions. Ground-dwelling rats and sciuromorphs feed on groundnuts, maize, sweet potato, yams and other crops. Examples are *Xerus erythropus* in Nigeria (Funmilayo and Akande, 1977), and the same rat species that attack coconuts in the Pacific islands (Wilson, 1972) – which is sometimes severe and, in the latter situation, led to the abandonment of attempts to grow groundnuts in some localities (Wilson, 1969). Rodents in India, particularly the squirrel *Funambulus pennanti*, may remove 25% of planted groundnut seeds (Mittal and Vyas, 1992), and the summer crop may be left unplanted. A strong relationship of rat activity to the suitability of the surrounding vegetation is noted. All stages of soybean in India are subject to damage, mainly by *Millardia meltada*, and also by *R. rattus* and *B. bengalensis* (Patel *et al.*, 1992).

In eastern Africa, burrowing mole rats are serious pests of cassava tubers. The planting method can help to reduce attack, and the interplanting of fish bean (*Tephrosia vogeli*) has a marked deterrent effect (Sichilima *et al.*, 2010).

Up to 16% of ripening pineapples were damaged by *Bandicota bengalensis* and *R. rattus* in Bangladesh in a range of study plots (Posamentier, 1981). In commercial plantings in India, cardamom seed capsules are damaged by a range of ground-dwelling rats, gerbils and squirrels (Srihari and Chakravarthy, 1992), in particular *B. bengalensis*. Seed capsules may be emptied, over 12% in the worst cases. The plants too can be damaged, especially in the young stages.

Among tree crops, coffee is not intensively attacked (Posamentier, 1981), but berries may be consumed (Barnett and Prakash, 1976) and branches debarked (Wilson, 1972). Macadamia nuts are eaten by squirrels in Queensland, and in a series of 21 study areas, the consumption ranged from 0 to 83% per tree (White *et al.*, 2003). Mean loss was significantly higher on plots adjacent to wider (10 m) strips of grassland (9.9%), than where the grass was regularly cut back (0.8%), with intermediate conditions within this range. This pointed to habitat manipulation as a means of control. Cashew fruit is damaged by a range of rodents in India (Keshava Bhat, 1992a), in particular by *B. bengalensis* and *Rattus blanfordi*. The young trees in forestry projects and rubber plantings may be lost by rodent grazing throughout this climatic zone and, while the incidence of damage is sporadic, losses can be severe where rodent grazing occurs.

Hystricomorphs can damage these crops as well as young tree plantations. Generally the pattern is for sporadic attack, but with heavy damage in relatively large patches (e.g. *Rhizomys* spp. and *Hystrix brachyurus* in the Far East, *H. indica* in the Indian subcontinent and *Thryonomys swinderianus* in West Africa).

Synthesis

Scope

We introduced this chapter by referring to the increasing appreciation of the need to understand the basic ecology of rodent pests, and to incorporate that into management practice. We have covered a broad range of cases, and in this section, look for general principles at work.

Essential population ecology

Populations of organisms depend on the resources available. Resources comprise support, such as food, shelter and so on, and escape from opposing factors, including interspecific and intraspecific competition, and antagonists such as predators, parasites, diseases, etc. The balance between these governs the population size, while the potential reproduction rate always tends to exceed the loss rate. This potential is suppressed by the failure of new individuals to become established (recruited) into the population. This is conspicuously so in small rodents because of their fast reproductive rate; for example, in a detailed study of the population dynamics of *Rattus tiomanicus* in oil palm, the potential birth rate (from embryo numbers) manifestly exceeds the balanced loss and recruitment rate in a population stabilized at the resource limit (Wood, 1984b; Wood and Liau, 1984a,b).

The tendency to over-reproduce has various practical consequences. The most obvious is that a population can build up rapidly as the environmental resource increases. In rice areas that are seasonal, the growing crop provides more food, so that greater survival of young can occur. There may also be an increase in reproductive potential as individual vigour improves, but the evidence is that the spurt is because of a reduction in the suppression of recruitment. Thus, the principal rice rat of Southeast Asia, *R. argentiventer*, appears strongly seasonal but, if given a continuous supply of food, continues to reproduce (Lam, 1983). Of course, the early build-up depends on the size of the initial population, which may have a seasonal element, depending on the vegetation that was present before the crop was planted and in surrounding areas (the source).

A second consequence is the rapid recovery from a control measure, especially if significant numbers survive it. In the more stable environment of oil palms, the balanced population was regained, after near total elimination, in about 18 months (Wood and Liau 1984a). The rodent population in grassland in China recovered from effective control within one summer season (Zhong *et al.*, 1999).

Another consequence is that the most competitive species will prevail and appear to be the characteristic rat of a particular agroecosystem but, where it is absent, other species can build up and be equally damaging. This may be obvious, like the absence of *R. argentiventer* on some Philippine islands, or more subtle, like the replacement of that species as rice planting moves into different ecosystems, into Thailand and further distant territories. The surprising replacement of *R. tiomanicus* by *R. r. diardii* in oil palm in Malaysia is of relevance here. At the time, *R. tiomanicus* had become warfarin resistant in the locality. Possibly, *R. r. diardii* could outcompete *R. tiomanicus* if the gene pool of *R. tiomanicus* was generally 'weakened' by the rapid evolution of the resistant strain (warfarin resistance is known to be associated with physiological costs in some populations of *R. norvegicus*; see Chapter 9). *R. tiomanicus* was known to have developed resistance to first-generation anticoagulants, and relativities between the species in this respect may be a factor. Perhaps more likely is that in palms virtually depleted of *R. tiomanicus*, *R. r. diardii* had an equal chance of repopulating the area, giving the opportunity for the evolution of palm-adapted strains.

A further consequence is that surplus individuals may disperse to find a niche in a suitable habitat. Most will perish eventually, but sometimes may first damage crops on which they can feed, but which would not support population build-up. Dispersal is continuous, but can be especially conspicuous when environmental support declines rapidly. Rats may then move in noticeable numbers, even giving an impression of invading these incidental crops. Lemmings (*Lemmus* spp.), for example, occasionally become agricultural pests when the end-of-season population crashes occur in northern latitudes (Batzli, 1975). Sometimes, rodents attack unusual crops in outbreak years, as in the case of *Apodemus* spp. on orchard trees in the former Yugoslavia (Rowe, 1968). Individual cases, of course, may involve particular complications that need to be assessed to determine the factors leading to population peaks and mass dispersal, e.g. in vole cycles (Ylönen *et al.*, 2003). A by now classic case is the prolific rodent upsurge at bamboo masting (Chauhan, 2003). Populations exist continuously in the bamboo forests, at numbers regulated by the (relatively low) amount of food available. Ripening crops in the locality present a suitable habitat for rodents only for short periods each year, so the opportunities for rapid population increase are limited. At masting, there is a huge population build-up, but equally, as the extra food disappears, so the excessive numbers of rats starve, leaving numerous corpses.

The periodic eruptions described above may be associated with particular weather events, generally unusually wet or dry periods, causing a flush of source vegetation for the rodent pests. The outbreak years of *Mastomys natalensis* in Tanzania are clearly related to early rainfall, which gives rise to the build-up of rodents before the crops are planted (Leirs *et al.*, 1997). Similarly, mouse plagues in Australia spread to crops as natural food supplies increase when suitable conditions prevail (Brown *et al.*, 2010). Variations in rodent outbreak and damage incidence in several crops around the Pacific are attributed to the El Niño and La Niña climatic events, acting via their effect on the abundance of source vegetation.

The importance of small rodents (mainly myomorphs) as pests particularly relates to the population dynamics that have been discussed. In ecological terms, they are *r-selected*; that is, they possess all or most of the following characteristics: short generation time, small size, high level of dispersal, low survival rates and high fecundity (see Chapter 1). The females typically start producing litters before they are 6 months old and can produce eight litters a year, each with between four and 12 young. This accounts for the rapidity of population responses to resource changes, as covered above. In the previous edition of the book, it was noted that much of the early work on the population dynamics of small rodents was in temperate countries in natural environments where numbers tend to be strongly cyclical. Since then, advances have continued to confirm that similar principles apply across the range of ecosystems, and important practical advances in tropical crops are covered here. Note that it is the situations that differ rather than the biological responses of the rodents.

Dispersing or ranging rodents may regularly penetrate crops that supply bulk food but do not support a resident population, if they grow bordering vegetation or crops that do so. In Asia, cocoa alongside oil palms (Wood and Chung, 2003) or rice (Baco *et al.*, 2010) can be very heavily damaged by rats, although further away from these crops, it is free of them. Cocoa also may be continually damaged by rats when the crop is interplanted with coconuts. Grass and sedge in China may sustain economic damage only when weeds suitable for their feed are present (Zhang *et al.*, 2003c). Further, rodents from source vegetation may find opportunity to attack crops that are suitable at only certain stages of their growth (Leirs, 2003). Examples include multimammate rats in Africa, which take only newly planted maize seeds and then exist on other food until the cobs form (Makundi *et al.*, 1999), or *Apodemus sylvaticus*, which attacks only newly sown sugarbeet seeds (Pelz, 1989).

Larger rodents generally exist in less dense populations of longer-lived individuals. They may have a lower capacity for rapid response to environmental change but, nevertheless, population size still is governed by resource. The ground squirrels of North American rangeland build up to high populations that exploit the environment to the full, but the increase is over a relatively long time (Marsh, 1984). Generally, such species tend to be restricted to more stable environments. Hystricomorphs also reproduce slowly and the severe damage that they inflict is often due to the large amounts eaten by individuals. Generally, they inhabit natural vegetation and damage to cultivation is sporadic, and mainly around the edges.

Rodent pests are generally indigenous species, though the foregoing examples include some that were introduced in the distant past, but which are now well integrated into the native fauna. More recent introductions have also found niches (e.g. the coypu and muskrat in Europe), but their initial hold may be tenuous enough to permit success in concerted attempts at elimination.

There is evidence that the rapid loss and increase rates in rodent populations lead to a slow change in the gene pool of the population, so that different population levels may occur in response to similar environmental situations. The chief experimental evidence for this centres on various studies of the survival of populations in relation to natural food supplies (Spitz, 1967; King, 1983), experiments on supplementary feeding (Taitt and Krebs, 1981; Desy and Thompson, 1983; Flowerdew, 1987), and the slow fluctuation from 200 to 600 ha^{-1} of *R. tiomanicus* in the rather stable oil palm environment (Wood, 1984b).

Ecology of incidence and control

Rodent pest problems may be categorized as chronic, cyclic seasonal or episodic eruptions. Chronic infestation is characteristic of agroecosystems in stable climates without marked crop seasonality, such as tree crops in the tropics. Cyclic attacks may be fairly consistent from season to season, or may vary markedly in intensity. This category shades into the episodic eruptions associated with vegetation changes such as bamboo masting, or from irregular weather conditions increasing the favourability of source vegetation. These irregular eruptions may be local and serious to those affected but without large-scale repercussions, but there can be a widespread wipeout, resulting even in human mass starvation events (World Food Programme, 2009).

Control methods also can be categorized as culling (direct killing of existing pests), protection of the crop and reducing environmental suitability (minimizing the resident and/or source population). Culling includes physical methods like trapping (live traps, multiple capture, break-back traps, snares), hunting (often with dogs) and dealing with harbourage, such as burrows, by such measures as digging out, fumigating or flooding. Commonly, only a proportion of the rodents is taken, allowing rapid recovery. Timing is frequently unsatisfactory – culling is usually in response to obvious build-up, when damage has already been done and the rats have spread. Baiting programmes may be delayed by organizational difficulties, including receiving approval from the authorities. Small farmers may, in desperation, spread very toxic poisons, including insecticides mixed with used engine oil, e.g. in rice paddies (Sudarmaji *et al.*, 2003). Such methods are disastrous to the environment, and most probably they usually have little of the effect intended. For example, Wood (1969) in a replicated plot trial in oil palms tested the broadcasting of endrin (a highly toxic chlorinated hydrocarbon insecticide). The result was that more rats were found at the post-treatment check.

Systematic anticoagulant baiting can overcome some rodent pest problems, effectively controlling what would otherwise have been increases to damaging levels, particularly in oil palms. Programmes have been clearly shown to be effective in rice, but the application of anticoagulant baiting is rarely adopted in that or similar seasonal crops by farmers in the field. Disincentives include preference for acute poisons in order to see dead rats quickly (though bait shyness means that they rarely reduce populations to low numbers), various payment or subsidy issues and concern about the poisoning of non-target animals, with possible implications in conservation issues (Singleton *et al.*, 2007). Bait suitability can be particular to rodent species and circumstance (Zhang *et al.*, 1999). Large commercial manufacturers often promote their baits, which are made for multiple feed use, but which are often less attractive or effective under field conditions. Anticoagulant resistance and other sustainability issues arise in the long term, so that effectiveness may suddenly or progressively decline, and optimal results depend on close and well-trained technical supervision over large areas. This makes the technique particularly suitable for extensive plantations with central management. Increasingly, there are problems from behavioural resistance, in which usually attractive baits are not accepted by rats in the field (Chung, 2011).

Protecting the crop may entail attempting to scare rats away. Disturbances such as moving around fields at night, possibly with dogs, shouting, banging, etc., may help, but are usually in the face of high populations and are a losing battle. Desperate rice farmers are known to resort to crude electric wires at field margins, even though these can be lethal to humans and their draught animals (Quick and Manaligod, 1990; Sang *et al.*, 2003). Fences can be effective, and are well suited to protecting the early stages in rice, for example, provided the timing is correct (e.g. dela Cruz *et al.*, 2003). Similarly, they may be used in temperate field crops against cyclic vole attacks, while protection against voles attacking sugarbeet can be given by providing alternative food (Pelz, 2003). The interplanting of a deterrent crop might also help, such as the fish bean with cassava (Sichilima *et al.*, 2010).

Reducing environmental suitability for rodents and hence the threat that they pose has many aspects. The destruction of source vegetation or harbourage, as around rice fields, or of food sources within the crop, as in selective weed control in Chinese grassland, can have an important effect. The early destruction of populations, when they are still limited in number, can reduce threats in seasonal crops, such as flooding in rice areas or in farmland in the North China Plain, although it can, by forcing rodents to concentrate on higher ground, worsen the problem there (Brown *et al.*, 1999). An agronomically based policy, like stopping flooding, may worsen rodent problems, as in the arable crops of northern China (Zhang *et al.*, 1999).

Ecologically based rodent management (EBRM) is a system that has been formulated in the last two decades. It covers the manipulation of the agroecosystem to minimize pest population pressure. The essentials are to understand the ecology and population dynamics of the pest rodent, and to manipulate the environment in order to keep damaging populations below economic levels. Important to the concept is to minimize the use of chemicals (largely in baiting) and to limit direct killing to what is necessary (Singleton *et al.*, 1999a,b, 2007). EBRM seeks to avoid adverse side effects, particularly from chemical measures, and to maximize sustainability. The technique has been developed most widely and successfully in rice, where the removal of source vegetation can pay big dividends and the timing of culling is related carefully to crop circumstance. In oil palms, despite success by a baiting protocol based on rat ecology, there is renewed interest in investigating the impact of environmental factors on population size. Crop management systems that reduce rat numbers include the control of grazing to reduce rodent populations in grassland in China, and land ploughing against (primarily) *M. natalensis* in East Africa (Leirs, 2003; Massawe *et al.*, 2003). In the same category are synchronous cropping in rice in the Far East, and adjusting for the severe attacks by *Microtus guentheri* in Israel that occur in lucerne continuously planted under irrigation. An interesting example of grazing affecting rodent populations was that of deer in Britain. In exclosures, there was a marked build-up of usually scarce to absent wood mice and bank voles (Dolman *et al.*, 2010).

Ecologically based systems that do not entail environmental modification include chemosterilization and infection (which both could be based on existing baiting techniques). Fertility control is being tested in the Qinghai–Tibet plateau because killing rodents is counter to local Buddhist philosophy, while the current rodenticide, botulin toxin C, raises considerable concern over its safety for non-target species, including livestock. Research on pikas has focused on quinestrol (synthetic oestradiol), levonorgestrel (synthetic progesterone) and a combination of both. Replicated field trials with the placement of baits at burrow entrances indicate that quinestrol shows good potential, with effects carrying across two breeding seasons (Liu *et al.*, 2012). Follow-on work is needed on the effectiveness of control on grass biomass, and whether there is compensation in breeding or survival at a given population level.

Biological control

Lists of predators are always interesting. In West Java, for example, there are rat snakes (*Ptyas korros*, *Coluber radiatus* and others), the mongoose, *Herpestes javanicus*, and the fishing cat (*Felis viverrina*) (Leung *et al.*, 1999); in India, there are predators of snakes, including raptors and monitor lizards (Sridhara, 1992). Generally, there is no strong evidence that predators can directly keep rat populations in check (Wood, 1985; Baker *et al.*, 2007). The evidence did not support predator destruction as a cause of rodent outbreaks after cyclone Nargis; instead, these were attributed to the disruption of crop synchrony (Htwe *et al.*, 2013). Barn owls, which are established in several oil palm plantations, can be established in rice and they eat rats, but there is no evidence yet that they affect population size (Hafidzi and Na'im, 2003).

Rats are also subject to a wide range of parasites and diseases. At present, a bait carrying sporocysts of the protozoan *Sarcocystis singaporensis* has been developed commercially (Jäkel *et al.*, 2006). Various helminths afflict rodents (e.g. Herawati and Sudarmaji, 2003) and might be used in a similar way, although they might be less species specific than is *Sarcocystis*.

Economics

Even though the understanding of rodent ecology as the basis for best management practice is increasingly appreciated, it needs to be linked closely to the economy of control measures (Stenseth *et al.*, 2003). This implies determining both the type and the cost of interventions. Estimating the size of the rodent population is important to the ongoing assessment of losses. Live trapping techniques (CMR) have given valuable insights in short- and long-term studies (Aplin *et al*., 2003). Such investigations are not always straightforward. Some rats are difficult to trap, notably *R. argentiventer*, the most important rice rat in many areas, and it is even more wary of being retrapped. Estimation by other methods may work, as with this species, in which after a period of CMR, an index capture was shown to be possible by hunting, following a plough, or collecting corpses after poison baiting (Wood, 1971).

The number of rodents caught in mass hunting or trapping campaigns can give a useful comparative indication. Other techniques can help, such as the use of tracking boards, or activity signs like the number of burrows. With repetition, these can become better related to actual loss of crop and population size, so they give an increasingly valuable guide on what control measures are justified, especially if these are costly in operational terms. An example is whether to set up the TBS system in rice fields. The success of measures applied can also be judged from such techniques.

Some caution may be needed about the species and numbers of rodents captured. These do not necessarily parallel their ranking as pests. Detailed studies usually show that one species is in fact the most common and damaging in a particular crop situation. In Hawaii, sugarcane was found to be attacked by *R. exulans*, *R. norvegicus* and *R. rattus*, but the first is actually much the most damaging (Lindsey, 1969); similarly, *Bandicota bengalensis* is among several species attacking rice in Pakistan (Greaves *et al*., 1977). Generally, where more than one species is relatively common, they are filling different niches. For example, *B. bengalensis* damages sugarcane in Pakistan, whereas *Millardia meltada* appears to be mainly a scavenger (Smiet *et al*., 1980), and on sugarcane in Bangladesh, *B. bengalensis* feeds on the canes above ground, whereas the fossorial *Nesokia indica* attacks their subterranean parts (Posamentier and van Elsen, 1984).

The key issue is always the value of product loss, though quantification is often vague or subjective. The assessment of damage can be a useful guide to rodent activity, as in rangeland, rice, sugarcane, coconuts and temperate trees, and it may be possible to correlate the damage to the losses incurred (Chapter 10). The destruction of young trees obviously loses the cost of replacement, but there is also a time factor to maturity. Often, the link between apparent damage and crop loss is imprecise, especially where the vegetative part of the plant is eaten, rather than the commercial product. Damage may be disguised and difficult to measure, and there may be some plant recovery, but of varying real impact on yield. Often, large-scale figures are based on an averaging of judgements of varying reliability from area-wide surveys and questionnaires. It is important to relate observed damage to loss, in order to build up a picture over time. This can help to emphasize the overall seriousness of the problem (e.g. on the North American prairies). Inaccuracies can multiply in such cases and, generally, as knowledge builds up, earlier estimates turn out to have been conservative; rarely, it may point the other way; for example, there is some recent evidence that prairie dogs (*Cynomys* spp.) may improve pasture by increasing soil organic content and promoting the growth of new grass more suitable for cattle (Foster and Hygnstrom, personal communication). The tendency is to underrate the effect of animal feeding on plant productivity. The position becomes even more complicated when the effects are not simply loss of crop but environmental effects, such as burrowing, that affect drainage, erosion, compaction, damage to irrigation equipment, and so on. Sometimes loss may be less than the perceived plant damage, sometimes more, due to variation in recovery potential, time of damage and other complications. This is illustrated by the impact of EBRM in limiting rice loss from rat damage, and from the accrual of evidence that has given a ‘ready reckoner’ for loss at given damage intensities (Palis *et al*., 2010). The relationship of rat numbers to loss is not necessarily linear, e.g. in maize in Tanzania (Mulungu *et al*., 2003).

In general, the best assessment of the economic impact is a comparison of yields with and without rodent attack. This is more feasible in a crop with a measurable product at a single harvest time, like rice, and it can be achieved with poison baiting if a very effective method is available, or by exclosures. The differences reported in rice in South-east Asia can be surprisingly large (Wood, 1984a; Buckle, 1988). Occasionally, a natural comparison may be possible; for example, the change in tree regeneration patterns during the period when rabbit populations were severely reduced by myxomatosis (Gill, 1992a). Another approach, where there is variable attack, is to do a regression analysis of yields against a measure of damage. This should reliably indicate the loss potential so long as no damage has actually occurred on plots recorded as zero damage. Examples of the use of this method are in apples in Washington State (Askham, 1988) and sugarcane in Florida (Lefebvre *et al.*, 1978).

There are cases where the relationship between damage and rodent density is well worked out. Tanzanian researchers and their overseas collaborators have approached the development of control of *M. natalensis* in maize through studies of population ecology and density–damage relationships in order to reduce populations to below 20 ha^{-1} (Skonhoft *et al.*, 2006). This has led to a prediction model for rodent population dynamics and the economics of control strategies for the whole region (Leirs *et al.*, 1996). Even so, more needs to be done to integrate the social elements of rodent management (Makundi and Massawe, 2011), including better understanding of the knowledge, attitudes and practices of farmers in relation to rodent management.

In some crops, the product is only a part of the harvested material, and loss, although it might be substantial, is difficult to estimate accurately. This is particularly so in some tree crops, where space rules out replication of ‘with’ and ‘without’ rodent plots. In oil palms, the estimated population size multiplied by the amount eaten by individuals has been taken to give a reasonable guide to economic threshold numbers.

Where attack is irregular both in time and severity, the potential usefulness of forecasting is self-evident. The value of total loss as around a masting event or some other cause is obvious as, similarly, is crop foregone (i.e. not planted). The only economic response is to avoid wasting effort and, here too, prediction is important. The monitoring of population size would give an ideal guide to expected loss, but would be costly and require some expertize. Two-tiered systems, with general observation and more intensive recording at critical times, can be developed in such cases.

Objective studies more often than not reveal much higher losses than expected. Further complications include downgrading of the quality as well as the quantity of crop. The need for complete resowing beyond a certain level of damage (for example in sugarbeet), the cost of replanting trees and the effect of delays in fruit bearing add to the economic effect of direct yield loss.

Practicalities of implementation in the field

Farmer attitudes play a big part in crops grown on a smallholder basis (see Chapter 14). Farmers may be amenable to any recommended approach, including area baiting programmes, accepting their effectiveness but even so expecting campaigns to be subsidized (Palis *et al.*, 2010). Individual preferences based on varying degrees of objectivity can come into play. Worries may concern such details as trap theft, and coordination among fellow growers (Morin *et al.*, 2003), and farmers may be imbued with country folklore, partial knowledge, religious or superstitious issues. Despite convincing trial results in practical conditions, measures are commonly not adopted in wide practice. One notable exception is the Mekong Delta in Vietnam, where there is strong extension support (Huan *et al.*, 2010). It becomes a question of education and effective communication, underpinned by extension support (e.g. Flor and Singleton 2010), and getting the growers involved in the trial situations (experiential learning) (Palis *et al.*, 2010), with coordinated effort to link potential to realization (adaptive management) (King *et al.*, 2003).

Education can be especially important within a complex of small farmers, who might perceive a benefit from doing nothing while those around them bear the costs, or alternatively might think that others take advantage from what they themselves do. Large-scale organizations do not have this problem so much but, even so, knowledge of best methods through extension training may be lacking.

Idiosyncratic preconceptions, some factually based, others more tenuous, may have to be dealt with in determining policy. This is especially the case in rice, which is commonly grown contiguously by a large number of small farmers (Singleton *et al.*, 2003c). These preconceptions include such beliefs as that rodenticides cause rodents to attack with a 'revenge' motive (Baco *et al.*, 2010). Where farmers are well informed and can be brought into operational planning, success is more likely to follow (Palis *et al.*, 2011). EBRM has progressed in Tanzania (Makundi and Massawe, 2011), but the authors stressed that more effort is required to understand better the knowledge, attitudes and practices of farmers relating to rodent management, and the social factors that can promote or hinder coordinated community-management actions for smallholder farmers. This necessity is also recognized in China (Du *et al.*, 2003).

Competence of personnel

Despite the advances in ecological knowledge encapsulated in EBRM, there remains a shortage of technical support at the field level. Courses in crop protection tend to concentrate on invertebrate pests, especially insects, whereas rodent biology is left to more academic studies that may lack a clear focus on practical ecological manipulation. All too often, control is equated with killing, and the bases of EBRM and integrated pest management (IPM) are left to one side. Improvement in the understanding of such matters would result in faster progress to discovering and implementing sustainable solutions.

Conclusion

Rodents can pose major threats to crop production, sometimes strikingly obvious, sometimes more cryptic. Awareness of their biology can improve the prospects for their management. As control practice comes to accord more closely with established ecology, the two aspects develop in tandem. The outcome is more sustainable pest control and more favourable economics. As we have attempted to demonstrate, there is a constant need to be aware of rodent problems and to search for control methods that optimize return on the effort and material costs involved.

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4 Rodents as Carriers of Disease

S.A. Battersby
Robens Centre for Public and Environmental Health and Environmental Regulatory Research Group, University of Surrey, Guildford, UK

Introduction

In the human mind, it seems, rodents have always been associated with disease. This no doubt is because of the association, over the centuries, of rats with bubonic plague and the 'Black Death', which was one of the deadliest pandemics in human history and peaked in Europe in the mid-14th century. The Black Death is widely thought to have been an outbreak of bubonic plague that transmuted into the pneumonic form. This disease led to the death of nearly a third of the human population, and in some parts of the world it is still causing illness and death (Keeling and Gilligan, 2000). As a result, the disease left an indelible mark on the development and social history of Europe. Its effects can be seen in literary references, including the poem by Robert Browning of the Pied Piper of Hameln, which came from a much older legend in Germany concerning the disappearance or death of a great many children from the town. Although not as closely associated with plague as rats, the house mouse is still an unwelcome pest in any household, and it carries with it the social stigma of lack of hygiene, lack of cleanliness and squalor and, as this chapter shows, is more than just a 'nuisance'.

Synanthropic Rodents, Zoonoses and Disease Transmission

Rats, particularly the Norway rat (*Rattus norvegicus*) and the roof rat (*Rattus rattus*), and house mice (*Mus musculus/domesticus*) are often thought of as commensal rodents because of their close association with human activity. In an ecological sense, the term commensalism refers to a more symbiotic relationship whereby one participant benefits while the other is neither benefited nor harmed. Commensal rodents benefit from their association with people in that they share dwellings with human occupants. Humans, though, not only do not benefit from an association with these rodents, they may also suffer harm. The primary concerns for environmental and public health are synanthropic rodents – that is, rodents associated with people or human dwellings. For example, in the USA, *R. rattus* is known as the roof rat because it prefers to nest in dry areas above ground – not only in nests constructed from grass and twigs in trees, but also in other elevated locations, such as roofs.

However, it is not just the Norway rat, roof rat and house mouse that are synanthropic rodent carriers of disease, even though they are among the most important. In the USA, the deer mouse (*Peromyscus* *maniculatus*) is considered to be the primary reservoir of the hantavirus that causes hantavirus pulmonary syndrome (HPS); human contact with fresh rodent urine, droppings, saliva or nesting materials can place that person at risk for infection, as recent cases in Yosemite National Park in California have shown. The cotton rat (*Sigmodon hispidus*), rice rat (*Oryzomys palustris*) and the white-footed mouse (*Peromyscus leucopus*) are also known to be carriers of hantaviruses (see below). On the Indian subcontinent and into South-east Asia, *Bandicota bengalensis* (the Indian mole rat or lesser bandicoot rat) is an important synanthropic rodent and a reservoir of a number of serious infections, including murine typhus and plague; it is also a common species with a growing population. In Africa, various species of the genera *Mastomys* (syn. *Praomys*) and *Arvicanthis* live in close association with human dwellings and carry a range of diseases.

More recent research studies have demonstrated that rodents can be infected with a larger number of organisms that cause illness in humans than had been previously thought – these are termed zoonoses. Zoonoses are defined by the World Health Organization (WHO) as those infections that are naturally transmitted between vertebrate animals and humans (WHO, 2012). Rodents may act as reservoirs of infection, harbouring organisms that cause disease and serving as potential sources of disease outbreaks. They may act as carriers and vectors of disease. As carriers, the rodent shows no or limited symptoms but carries the disease-causing agent, which can then be passed directly to humans. Rodents may also act as vectors in the mechanical transmission of disease when fur and feet come into contact with contaminated substrates and these move with the rodents from one place to another.

Rodents are a hazard to health because they can amplify pathogens from the environment and form reservoirs of (zoonotic) disease (Webster and Macdonald, 1995; Battersby *et al.*, 2002). Rodents can spread pathogens directly to humans, for example via bites, or indirectly via food products or water that are contaminated with rodent faeces or urine (e.g. leptospirosis). It is also possible to inhale organisms present in airborne fragments of rodent faeces that contaminate the environment (e.g. hantaviruses) (Meerburg *et al.*, 2009). Bregman and Slavinski (2012) found that, annually, up to 7% of visits to New York City Emergency Departments because of animal bites were for rat and mouse bites.

Rats have been implicated in the spread of murine typhus, plague, salmonellosis, leptospirosis, trichinellosis and rat-bite fever (Haverhill fever). Over the last millennium, it has been estimated that rat-borne diseases may have taken more lives than all of the wars ever fought.

Where rodents acts as the disease reservoir, the rodent-borne disease may be transmitted to humans via an ectoparastic arthropod or livestock intermediary (Meerburg *et al.*, 2009). It has been shown that rodents can help to maintain pathogen transmission cycles in a variety of different environments, from densely populated urban areas to rural areas.

It should also be recognized that global climate change and changing human settlement patterns (including in developing countries) could lead to increased problems with rodent-borne pathogens because the distribution of rodent species, arthropods and, thus, also pathogens of these species, could be greatly affected (Bonnefoy *et al.*, 2008). For example, it has been shown that *Yersinia pestis* prevalence in gerbils in Central Asia increases with warmer springs and wetter summers. Threats of outbreaks may therefore be increasing where humans live in close contact with rodents and fleas (or other wildlife) that are harbouring endemic plague (Stenseth *et al.*, 2006).

Rodents carry and transmit a vast array of diseases to humans and their domesticated animals. In a review of these zoonoses, Meerburg *et al.* (2009) listed 20 viral diseases, 19 bacterial diseases, six protozoal diseases and 16 pathologies caused by helminths. Among these, 18 were considered to have a severe impact on human health. Although rodent-infested urban premises are more likely to be found in poorer areas, the risk to public health only arises if the rats are carrying arthropod vectors of disease or are themselves excreting disease-causing organisms.

It may be argued that, given recent studies, concern about rodents in the developed world has become more an issue of public health, yet the epidemiology of many zoonotic diseases is poorly understood. Even in the UK, baseline data on the prevalence of important zoonoses in wildlife are scarce (Battersby *et al*., 2002). A key message to emerge from many studies is the underreporting of rodent zoonoses and that, in many cases, insufficient attention is paid to the diagnosis of these important diseases. It is suggested that in developed countries, where there is overproduction of food crops and adequate storage, justification for rodent control is on grounds of hygiene, public health and animal hygiene, rather than for economic reasons, whereas in the tropics and subtropics the opposite is more likely to be true.

Table 4.1 summarizes the human diseases that have been shown to be associated with rodents. The diseases are discussed in the following sections.

Ectoparasites and Disease

Parasites that live on the skin and fur of rodents – ectoparasites – have the potential to cause health problems for humans. In the UK, and probably elsewhere, ectoparasites are not considered to be a significant public health problem in the absence of disease-causing organisms, though bites may cause localized skin irritation and, occasionally, more severe dermatitis. In a sample of 510 farm rats (Norway rats), Webster and Macdonald (1995) found that 100% carried fleas, two thirds carried mites and 38% carried lice, but none was found to carry ticks. Stojčevič *et al*. (2004) found that 82 out of 255 rats (32.2%) trapped in Croatia were infected with ectoparasites (fleas, lice and mites).

Such ectoparasites carried by rats do not directly cause illness in humans or domestic animals, but as vectors, they are responsible for serious diseases of humans in many countries. Bubonic plague is the most widely known example; in this disease, the vector is the Oriental (or Asiatic) rat flea, *Xenopsylla cheopis*. Despite a high prevalence of ectoparasites such as fleas, mites and lice on rats, they appear currently to represent little risk in the developed world in the absence of primary pathogens such as *Y. pestis*, the rickettsiae and viruses causing haemorrhagic fevers. However, that is not true elsewhere, as will be shown below.

Ticks

Ticks can be vectors for *Borrelia* and *Babesia* in the UK, although in the study by Webster and Macdonald (1995) mentioned above, no ticks were found on the sample of farm rats tested. Another study (Matuschka *et al*., 1997) did find that subadult ticks attached readily to *R. norvegicus*, as well as to *R. rattus*, and that virtually all became infected in the course of feeding. Larval ticks detached when these nocturnally active hosts were at rest. So rats would appear to be competent reservoir hosts of Lyme disease spirochaetes (*Borrelia burgdorferi*) in a transmission cycle in urban sites. Many rodent and lagomorph species appear to serve as sources for infected blood-feeding ticks, fleas and other ectoparasites. In the case of Lyme borreliosis (LB), *Ixodes* ticks can transfer the causative agent from spirochaete-infected mice, or other non-commensal rodent hosts, to people. Still other tick species that feed on rodents and lagomorphs are vectors of the spotted fever group rickettsiae in Europe or North America (Gage and Kosoy, 2008).

Mites

Different mite species found on animals may temporarily also infest humans. Consequently, these arthropods may be responsible for pruritic skin reactions (itching) that may be misdiagnosed. Mite dermatitis caused by the tropical rat mite, *Ornithonyssus bacoti*, occurs in several small mammals and rodents in tropical and temperate climates. According to various observations in Germany, *O. bacoti* appears in wild rodents more frequently than previously thought. The diagnosis of rat mite dermatitis requires identification of the parasite, which is more likely to be found in the environment than on the hosts' skin. Beck and Pfister (2004) reported on five outbreaks in Germany.

Table 4.1. Summary of diseases associated with rodents (primarily *Rattus* spp. and *Mus* spp.). (Adapted from Battersby *et al*., 2008, and other sources.[a])

Human disease	Vector, pathogen or both
Ectoparasites	
Bubonic plague	Asiatic/Oriental rat flea (*Xenopsylla cheopsis*) – *Yersinia pestis*
Lyme disease	Ticks (*Ixodes* spp.) – *Borrelia burgdorferi*
Murine typhus[b]	Asian/Oriental rat flea – *Rickettsia typhi* (Human) body louse – *R. typhi*
Rickettsialpox[b]	Rodent mite (*Liponyssoides sanguineus*) – *Rickettsia akari*
Tick-borne relapsing fever (TBRF)	Ticks (*Ornithodoros hermsi*) – *Borrelia* spp.
Endoparasites	
Amoebic dysentery	*Entamoeba* spp. (e.g. *E. histolytica* and *E. muris*)
Angiostrongylosis[*]	*Strongyloides* spp.
Babesiosis	*Babesia* spp.
Capillariasis	*Capillaria* spp.
Coccidiosis	*Coccidia* (*Eimeria*) spp.
Cryptosporidiosis[b]	*Cryptosporidium parvum*
Diarrhoeal disease	*Hymenolepis* spp.
Diarrhoeal disease	*Trichuris* spp.
Diarrhoeal disease	*Taenia* spp.
Rat tapeworm infection	*Hymenolepis nana*
Sarcosporidiosis	*Sarcocystis* spp.
Schistosomiasis[†]	*Schistosoma* spp.
Toxocariasis	*Toxocara* spp.
Toxoplasmosis[b]	*Toxoplasma gondii*
Trichinellosis[‡]	*Trichinella* spp.
Bacteria	
Diarrhoeal disease	*Vibrio* spp.
Escherichia coli 0157/VTEC*	*E. coli* 0157
Leptospirosis[b] (Weil's disease)	*Leptospira* spp.
Listeriosis	*Listeria* spp.
Melioidosis	*Pseudomonas* spp.
Pasteurellosis	*Pasteurella* spp.
Q fever	*Coxiella burnetii*
Rat-bite fever (and Haverhill fever)[b]	*Streptobacillus moniliformis* and *Spirillum minus*
Salmonellosis[b,§]	*Salmonella* spp.
Tularaemia[‡]	*Francisella tularensis*
Yersiniosis	*Yersinia enterocolitica*
Viruses	
Haemorrhagic fever with pulmonary syndrome (HFPS)	*Sin Nombre virus* (Hantaviridae)
Hantaan fever (haemorrhagic fever with renal syndrome, HFRS)	*Hantavirus* (Bunyaviridae)
Lassa fever	Arenaviridae virus
Lymphocytic choriomeningitis[c,#]	*Lymphocytic choriomeningitis virus*

[a] From: Webster and Macdonald (1995) and Battersby *et al.* (2002), excepting the following: [*]Meerburg *et al.* (2009); [†]Gratz (1984); [‡]Nowak (1999); [§]Seguin *et al.* (1986) and Hilton *et al.* (2002); [#]Lehmann-Grube (1971).
[b] Indicates zoonoses of both house mice (*Mus musculus/domesticus*) and *Rattus* spp.
[c] Indicates zoonosis only of house mice.

A clinical example from this study was the case of a 23-year-old medical student and several other residents inhabiting a rat- and mouse-infested house in Munich. Mites were found in large numbers in the student's flat. The patient was suffering from severe itching and papular urticaria. The dermatitis was misdiagnosed as an allergic response and treatment with an anti-inflammatory agent was unsuccessful.

Lice

Louse-borne relapsing fever (LBRF) is caused by bites from the human body louse (*Pediculus humanus humanus*) infected with *Borrelia recurrentis*, whereas tick-borne relapsing fever (TBRF) is caused by one of several *Borrelia* spp. infecting soft-shelled ticks of the genus *Ornithodoros*. Borreliosis, and most *Borrelia* spp., along with their rodent-borne arthropod vectors, are distributed in North Africa, from the Caucasus to Iraq and Central Asia, and in North and South America. *B. hispanica*, vectored by *O. eraticus*, is found in Spain and Portugal causing Hispano-African TBRF. Other diseases for which rodent ectoparasites are vectors include murine typhus, rickettsialpox and spotted fevers (Padovan, 2006).

Fleas

The association of fleas with the transmission of the causative organism of bubonic plague, the bacterium *Y. pestis*, makes them one of the best-known ectoparasitic arthropod vectors of human disease. However, fleas also transmit many other zoonotic organisms to humans, companion animals and domestic livestock; these include organisms causing a variety of viral, bacterial and rickettsial diseases, as well as certain protozoal and helminthic disorders (see below).

Rickettsial diseases and mites

The rickettsiae comprise a group of microorganisms that occupy a phylogenetic position between bacteria and viruses. They are obligate intracellular Gram-negative coccobacilli that multiply within eukaryotic cells. A general characteristic of rickettsiae is that mammals and arthropods are natural hosts. In a study in Baltimore, Maryland, *Rickettsia typhi* was detected in 7% of Norway rats (Easterbrook *et al.*, 2007).

A disease that is associated with urban environments is rickettsialpox. The causative organism of this disease, *Rickettsia akari*, is transmitted to humans by rodent mites. The pathogen is maintained by vertical transmission (i.e. from parent to offspring) in the house mouse mite (*Liponyssoides sanguineus*) and by horizontal transmission between the mite and its main host, the house mouse. Meerburg *et al.* (2009) also reported studies in which the pathogen was isolated from synanthropic rats in Ukraine, from roof rats, dusky-footed woodrats (*Neotoma fuscipes*) and deer mice (*P. maniculatus*) in the USA, and from Korean reed voles (*Microtus fortis*) in Korea. This suggests that *R. akari* can adapt to other rodent hosts. Human infections have been reported in the USA (e.g. Paddock *et al.*, 2003; Bennett *et al.*, 2007).

With rickettsialpox in humans, there is a cutaneous lesion at the site of inoculation by the mite. A papule appears first and later this evolves into dry scab or eschar. After about 1 week the patient develops fever, chills, malaise and headache, followed shortly by a secondary papulovesicular cutaneous eruption (a rash characterized by both papules and vesicles) (Heymann, 1996). In common with many rat-borne diseases, rickettsialpox is infrequently reported and underdiagnosed (Meerburg *et al.*, 2009).

Murine typhus can be caused by *R. typhi*, and rodents, more specifically rats (*R. norvegicus*, *R. rattus*, *B. bengalensis*), are associated with the worldwide distribution of the bacterium (see, for example: Reeves *et al.*, 2008; Meerburg *et al.*, 2009). The vector is the rat flea, *Xenopsylla cheopis*, and humans acquire the disease from an infected flea. Most fleas defaecate while biting and their faeces can contain the bacteria that cause the disease. Although uncommon, it is also possible for humans to contract murine typhus by inhaling contaminated dried flea faeces. The incubation period for the disease lies on average between 6 and 14 days. Symptoms include headache, fever, nausea and body aches. Respiratory and gastrointestinal symptoms are frequent and may result in confusion with a viral illness. The mortality rate for murine typhus is assessed at between 1 and 4%. This disease is also frequently underreported, and so it is difficult to provide reliable incidence rates. In the USA, about 42,000 cases were reported between 1931 and 1946, but incidence declined rapidly as a result of rat-control programmes (Meerburg *et al.*, 2009).

Rocky Mountain spotted fever and its infectious agent, *R. rickettsii*, are known only from North and South America, and are most common in the south-eastern states of the USA. The reservoirs of the infectious agent include many different animals, including rodents. The rickettsial causative agent may be found in different species of the genera *Microtus*, *Peromyscus*, *Sigmodon* and *Spermophilus*.

Endoparasites

Webster and Macdonald (1995) found that Norway rats in the UK were infected with 13 different endoparasitic organisms and other zoonotic agents, with some rats having infections of up to nine of these simultaneously. In a study of the Norway rat in Baltimore, Easterbrook *et al.* (2007) found that their endoparasites included *Calodium hepaticum* (syn. *Capillaria hepatica*) and *Hymenolepis* sp. Antibodies to Seoul virus, hepatitis E virus (HEV), *Leptospira interrogans*, *Bartonella elizabethae* and *R. typhi* were also detected. Since the 1990s, studies have extended our knowledge of the range of endoparasites infecting rodents.

Gratz (1984) included schistosomiasis as one of about 40 diseases in which rats are carriers, and as many as 200 million people worldwide are infected with this disease. Table 4.1 provides a summary list of the endoparasitic diseases associated with rodents, and in particular with *R. norvegicus*, *R. rattus* and *M. musculus*.

The relationships between endoparasites and their hosts are complex and poorly understood. For example, and as an indication of this complexity, MacDonald *et al.* (1999) reported that rats exhibited behavioural changes caused by infection with *Toxoplasma gondii*. They became less wary of predator odours and therefore more susceptible to predation, thus facilitating the transmission of *T. gondii* to cats, the definitive host, and increasing the risk of transmission to people.

The number of the endoparasites found in rodents indicates the nature of the potential risks to health. For example, a study in Jamaica on the distribution and zoonotic potential of gastrointestinal helminths in a naturally infected population of wild rats (*R. rattus* and *R. norvegicus*) found that some 29.7% of 437 rats captured were infected. Nine species of gastrointestinal helminths were recovered: *Raillietina* spp. *Trichuris* spp., *Rictularia* spp., *Syphacia obvelata*, *Strongyloides ratti*, *Hymenolepis diminuta*, *Protospirura muricola*, *Moniliformis moniliformis* and *Nippostrongylus brasiliensis*. *H. diminuta*, *M. moniliformis*, *Raillietina* spp. and *Rictularia* spp. are potentially zoonotic, but only infection of humans by *H. diminuta* had previously been reported in the Caribbean (Waugh *et al.*, 2006). In a study of the endoparasites of rats in Croatia, the most frequently found species was *H. diminuta*, with 36.9% of rats infected (Stojčevič *et al.*, 2004). The prevalences of other endoparasites were: *Heterakis spumosa*, 25.9%; *N. brasiliensis*, 16.9%; *Calodium* (syn. *Capillaria*) spp., 18%; *Taenia taeniaeformis* (larvae), 10.6%; and *S. ratti* 1.18%. *C. hepaticum* was found in the liver in only one animal, a very different finding from that of other studies. In a study by Conlogue *et al.* (1979), 82% of 86 Norway rats trapped in Hartford, Connecticut, between February and November 1975 were found to be infected with *C. hepaticum*. In the study by Easterbrook *et al.* (2007) in Baltimore, the following prevalences of endoparasites were found in Norway rats: *C. hepaticum*, 87.9%; and *Hymenolepis* spp., 34.4%.

Nematodes (roundworms and threadworms)

Calodium and capillariasis

Calodium spp. are liver nematodes that have rats and mice as their main hosts but are found in many other animals. Hepatic capillariasis is a rare infection in humans that is caused by *C. hepaticum*, with perhaps no more than 40 cases recorded around the world. Transmission to humans from rats, for instance via faecal contamination of foodstuffs, is rare, although those few cases that have been reported have almost all been fatal. Classically, the disease has severe symptoms that mimic acute hepatitis. Natural reservoirs of *C. hepaticum* are urban rodents (*M. musculus/domesticus* and *R. norvegicus*) and the adult nematodes lay their eggs in the hosts' livers (Camargo *et al.*, 2010). Outside the UK, these roundworms have been found in wild rats at a high prevalence, and there is a worldwide distribution. Human intestinal capillariasis, caused by *C. philippinensis*, was originally reported in the Philippines and subsequently also in Thailand. The WHO says it is characterized by diarrhoea, malabsorption, fluid imbalance and a protein-losing enteropathy. Adult worms occur in the liver of rodents and other animals, and the eggs are dispersed from the liver on the death of the host. In Milan, Italy, out of a sample of 47 wild Norway rats, 17 (36%) were found to have liver lesions consistent with *C. hepaticum* infection (Ceruti *et al.*, 2001). This prevalence was higher than that in both rural and urban rats in England (Battersby *et al.*, 2002). The few cases of *C. hepaticum* infections in humans that have been documented worldwide were mostly in children from 1 to 5 years of age, but the potential transmission of *C. hepaticum* to children in Milan was considered an important health issue (Ceruti *et al.*, 2001).

Strongyloides (threadworm) infection

Several species of *Strongyloides* (threadworms) are common intestinal parasites of ruminants, pigs, horses and other mammals, and have been detected in rats. The infective third-stage larvae of *Strongyloides* spp. are able to invade the skin of humans and produce symptoms of cutaneous larva migrans. Strongyloidiosis is an intestinal parasitism caused by *S. stercoralis*. Humans are the host of *S. stercoralis*, which also occurs in primates, dogs and cats. It has a worldwide distribution, but is said to be more prevalent in tropical and subtropical areas. However, it has been found in Poland and therefore could spread in temperate zones after importation (WHO, 1979). Intestinal infection with *S. stercoralis* may be asymptomatic or associated with symptoms such as diarrhoea, nausea and malabsorption.

Although distributed throughout the humid tropics, *S. stercoralis* can be found in any temperate areas where poor sanitation and other factors facilitate the occurrence of faecally transmitted organisms. It is suggested that the growing importance of human strongyloidiosis depends upon the unique ability of *S. stercoralis* to replicate within its host and behave as a potentially fatal opportunistic pathogen in compromised hosts, particularly those receiving corticosteroids. Some 3 to 100 million people are estimated to be infected worldwide. It has now been found that foci of low endemicity exist in several industrialized countries in Western Europe, such as Italy, France and Switzerland (1–3% prevalence). *S. stercoralis* is present in virtually all tropical and subtropical regions of the world with a prevalence varying from less than 1 to 85% in populations living in adjacent regions of the same country. It has been a problem in animal populations, and is especially linked to dog breeding kennels. Transmission of *S. stercoralis* among both humans and animals can be prevented by measures to dispose of and treat excrement properly, and by avoiding contact with contaminated substrates such as soil and caging. Symptoms include abdominal pain, bloating, heartburn and brief episodes of diarrhoea. The majority of people with chronic infections are either asymptomatic or have mild non-specific symptoms.

Trichuriasis – whipworm infection

Trichuris trichiura is a nematode that has been thought only to infect humans. Trichuriasis is also known as whipworm infection, and affects the large intestine. In the UK, *Trichuris* spp. was the only parasite found to be more prevalent in urban than in rural rats (Battersby *et al.*, 2002), and at a prevalence of 15% compares with the prevalence of 6.6% for *T. muris* in a Turkish village (Carlson and Sahin, 1979). It is most common in the tropics and areas of poor sanitation, particularly among children, and worldwide there are an estimated 46 million infected people, with associated morbidity and an annual mortality of 10,000. Light infections are asymptomatic, but heavy infections cause diarrhoea, anorexia, gastrointestinal problems, finger clubbing, rectal prolapse and growth retardation. Infections are associated with poverty and poor living conditions, inadequate sanitation and water supplies, soil quality and climate, poor personal and environmental hygiene and poor health awareness.

Trichinellosis

Trichinella spiralis is the only species in the genus that is highly infective in swine and rats. Synanthropic animals such as rats can complicate the epidemiology of trichinellosis because they contribute both as a reservoir and as a link between domestic and rural or agricultural habitats. In contrast, some consider rats as a victim of domestic trichinellosis instead of acting as a reservoir; that is, infected rats exist because they are infected by pigs and not vice versa.

Toxascariasis and toxocariasis

In toxascariasis, it is usually cats, dogs, foxes and other carnivores that are the definitive hosts of the causative roundworm, *Toxascaris leonina*. After these carnivores ingest infective eggs, the eggs hatch and the larvae mature in the small intestine. Adult worms produce eggs that are passed via faeces to the environment. Rodents can act as intermediate hosts of these roundworms (Meerburg *et al.*, 2009). The rodent ingests the eggs, which hatch and the larvae migrate through the tissues of the rodent. If a carnivore eats the rodent, the larvae are released in its digestive system, thus completing the parasite's life cycle. Humans may acquire infection by direct ingestion of eggs. It is also possible, but rare, for children to be infected by handling infected kittens or puppies. *T. leonina* is a cause of visceral larva migrans in children, though it is less frequently implicated than is *Toxocara canis*, the roundworm that causes toxocariasis. *T. leonina* differs from other related species in that the larvae do not migrate through the lungs.

Cestodes (tapeworms)

Tapeworms of concern in human public health belong to the subfamilies Taeniae and Echinococcinae. The two most important tapeworms for humans are *Taenia solium* and *T. saginata*. Human cysticercosis is caused by the development of *T. solium* cysticerci in the tissues of humans. Tapeworms can be 40–100 cm long and inhibit the small intestines of the definitive host; the infection is called taeniasis. Adults are present in the intestine of carnivorous and omnivorous mammals, including humans, throughout the world. The level of involvement of rodents in human infection depends on the *Taenia* spp. that is contracted.

Rodents (and also lagomorphs) are intermediate hosts of metacestodes of *T. multiceps* and *T. serialis* and contribute to the life cycle of this parasite. *T. taeniaeformis* is a parasite that is present in rodent intermediate hosts and definitive hosts of the cat family, but human infections have also been reported from Argentina, Japan and Sri Lanka (Meerburg *et al.*, 2009).

Rodents also contribute to the life cycle of *Echinococcus multilocularis*, a tapeworm of 1–4 mm in length. Wild foxes, coyotes, dogs and cats are definitive hosts, and are infected when they eat *E. multilocularis* larvae in infected rodents (Meerburg *et al.*, 2009).

Hymenolepis spp. have been found in rural rats in the UK (Webster and Macdonald, 1995) and were also found in a study of urban rats in the UK (Battersby *et al.*, 2002). *H. diminuta* is the dwarf tapeworm and *H. nana* is the rat tapeworm. These cestodes both have rats as the principal host and both can infect humans, particularly children. Although there were no reports of direct cross-contamination between humans and rats according to Webster and Macdonald (1995), a study in Jamaica found that human infection with *H. diminuta* had been reported in the Caribbean (Waugh *et al.*, 2006).

Infection by *H. diminuta* is usually via the ingestion of infected intermediate host insects, while *H. nana* is generally contracted through eating contaminated faeces, and its life cycle can be completed in a single host.

Protozoa

Meerberg *et al*. (2009) list a number of rodent-borne diseases caused by protozoa of the classes Sporozoea and Zoomastigophorea; see also Table 4.2. Some of these are described below.

Cryptosporidiosis

Cryptosporidiosis, caused by the protozoan *Cryptosporidium* spp., causes illness after ingestion of the oocystic stage of the organism. Webster and Macdonald (1995) and Webster *et al*. (1995a,b) showed that *Cryptosporidium* is far more prevalent in rural rats than *Leptospira* spp., the organism that is perhaps most associated with rat-borne disease by the general public.

For *C. parvum*, Coop *et al*. (1998) report that the time between ingestion of oocysts and their appearance in animal faeces is between 2 and 12 days, depending on the host. In humans, the incubation period is 2–14 days and, in immunocompetent humans, causes an acute self-limiting gastroenteritis. Often initial or warning (prodromal) malaise occurs, with nausea and loss of appetite. This is followed by the onset of acute diarrhoea and other symptoms such as vomiting (in children), weight loss and abdominal pain. Webster and Macdonald (1995) suggested that wild Norway rats, as carriers, pose a risk to the health of humans and livestock. This is because only a small numbers of oocysts are required to initiate a clinical infection. Adult rodents have been observed to shed small numbers of oocysts in their faeces and, as such, are a significant potential source of infection on farms. This could be via contamination of feed, which could then pass into slurry, which may subsequently be spread on to farmland, with a potential for runoff into watercourses. It has also been suggested that ‘low grade’ sources lead to livestock neonatal infections, again because only small numbers of oocysts are required for clinical infection to occur. This may progress from neonate to neonate, and lead to the very high infection rates that have been observed on some farms.

Toxoplasmosis

Toxoplasmosis can be caused when a cat excretes *Toxoplasma gondii* oocysts, which are then ingested by other animals. Primary infection rarely causes symptoms severe enough to be reported. However, in the acute form, the patient may have a fever and enlarged lymph glands, and in immunocompromised patients the primary infection can cause more severe illness, affecting the brain, lungs and heart, and lead to death. Toxoplasmosis can

Table 4.2. Important protozoal diseases of humans with rodent reservoirs.

Disease (causative organism)	Geographical distribution	Main rodent reservoirs	Vector
Chagas disease (*Trypanosoma cruzi*)	Latin America	*Rattus* spp. and many others	Tritominae
Cryptosporidiosis (*Cryptosporidium* spp.)	Global	*Rattus norvegicus*, *Mus musculus*, *Microtus arvalis*, *Myodes glareolus*	
Leishmaniasis			
Visceral (*Leishmania donovani*)	Asia, Africa, Latin America	*Rattus* spp. and dogs	Sandflies
Cutaneous (*Leishmania* spp.)	Americas, Asia, Africa, Europe	*Psammomys*, *Arvicanthis*, *Rattus* spp., *Meriones*, *Oryzomys*, *Proechimys*, *Akodon*	Sandflies
Toxoplasmosis (*Toxoplasma gondii*)	Global	*Rattus norvegicus*, *Sigmodon* spp., *Mus musculus*	

cause mental retardation and loss of vision in congenitally infected children and death in immunosuppressed patients, especially those with acquired immunodeficiency syndrome (AIDS). Dubey (1998) described *T. gondii* as widely prevalent but, while warm-blooded animals can act as intermediate hosts, the life cycle can only be completed in cats. Eating infected mammals such as rats leads to infection in the cat, and the parasite then develops in the cat's intestines. Cats excrete oocysts (the resistant stage) of *T. gondii* in their faeces, and these can survive in the environment and remain infective for up to 18 months. Ingesting undercooked infected meat or food and water contaminated with the oocysts can infect humans.

Infection across the placenta by free tachyzoites also occurs in humans when a pregnant mother acquires the primary infection. The fetus can be affected at any stage of pregnancy, but the greatest risk is during the first trimester, when infection can lead to fetal death. There is no vaccine to control toxoplasmosis in humans.

Amoebiasis

Entozoic amoebae live within the bodies of their hosts. The majority belong to the family Entamoebidae, to which belongs the causative organism of amoebic dysentery in man, *Entamoeba histolytica*. Species of the genus *Entamoeba* live in the large intestine, apparently as harmless commensals, feeding on bacteria and forming cysts containing a number of nuclei. Amoebiasis is primarily associated with urban overcrowding and poor sanitation. The most common amoeba in rodents is *E. muris*, which lives in the caecum. This parasite is said to be morphologically indistinguishable from the closely related *E. coli* in humans.

Infection of rats with *E. histolytica* has been known since the early 20th century, although it infects humans and other primates predominantly. It is estimated that about 500 million people are infected with the parasite worldwide (Lucas and Upcroft, 2001) leading to 40,000 to 100,000 deaths annually. Amoebic dysentery is transmitted through contaminated food and water. Symptoms of infection can include fulminating dysentery, diarrhoea, weight loss, fatigue, abdominal pain, and amebomas (formation of annular colonic granulation and a large local lesion of the bowel). The amoeba can bore into the intestinal wall, causing lesions and intestinal symptoms, and it may reach the bloodstream, from whence it can reach different organs of the body.

Giardiasis

Giardiasis is a diarrhoeal illness caused by a flagellated protozoan parasite called *Giardia intestinalis* (also known as *G. lamblia* or *G. duodenalis*). The parasite is found on surfaces or in soil, food or water that has been contaminated with faeces from infected humans or animals. *G. intestinalis* is found worldwide. Acute symptoms of the disease include diarrhoea, upset stomach or nausea/vomiting, and stomach or abdominal cramps. Other symptoms include loss of appetite, lethargy, fever, stomach problems (cramps), bloating and flatulence.

The US Centers for Disease Control (CDC) has estimated that giardiasis infects nearly 2% of adults and 6 to 8% of children in developed countries worldwide and nearly 33% of people in developing countries. In the USA, *Giardia* infection is the most common intestinal parasitic disease affecting humans, who are infected by swallowing *Giardia* cysts in contaminated food or water. The cysts are instantly infectious once they leave the host through faeces.

Rodents may form a reservoir of infection and could cause contamination of watercourses with *G. lamblia* cysts. Meerburg *et al.* (2009) reported studies that identify muskrats (*Ondatra zebethica*), voles (various species), deer mice and yellow-necked mice (*Apodemus flavicollis*) as carriers.

Leishmaniasis

Human leishmaniasis infections are caused by one of several species of flagellate protozoans of the genus *Leishmania*. Two forms of the disease occur, cutaneous and visceral, of which the latter is the most clinically severe. Cutaneous leishmaniasis is caused by one of many leishmanias, including *L. major*, *L. tropica* and *L.* (syn. *Viannia*) *braziliensis*, that occur very widely in tropical, subtropical and arid regions of the Old and New Worlds. Clinical presentation is of cutaneous lesions, often of the face, some of which may be persistent and severe. The efficacy of treatment is dependent on the correct identification of the causative organism and requires the administration of drugs that may have significant side effects. Visceral leishmaniasis, or kala-azar, is caused by *L. donovani* and *L. infantum*, and occurs in a variety of forms in Asia, the Mediterranean and Latin America. Symptoms include weight loss, fever, oedema, dysentery and malaise. Without treatment, prognosis is poor and death frequently occurs. When treated, outcomes are highly variable depending on the time of diagnosis and efficacy of the treatment regime (Gonzales *et al*., 2008). In recent times, the epidemiology of the disease has been much influenced by wars and other social strife.

The vectors of all species and forms of *Leishmania* parasites are phlebotomine sandflies. Rodents are often fundamental to disease transmission as reservoirs because sandflies breed, rest and feed in rodent burrows. Thus, rodent-control programmes may form part of the disease management strategies (Anonymous, 2008). The rodents involved in transmission include the gerbil, *Psammomys obesus* (Saudi Arabia, Israel, Algeria and Libya), *Meriones* spp. and *Arvicanthis niloticus* (in other parts of Africa), and *Oryzomys* spp. and *Akodon* spp. (in Latin America). Dogs are usually the most important peridomestic hosts of visceral leishmaniasis, but in some areas several species of *Rattus* have been implicated.

Trypanosomiasis

Chagas disease is an illness restricted to the Americas, mainly the countries of Latin America, caused by the trypanosome protozoan *Trypanosoma cruzi*. The causative organism occurs in many vertebrate reservoir hosts and is transmitted to humans by the bites of triatomine hemipterans known locally as assassin and kissing bugs. In man, the disease has acute and chronic phases; the former mainly occurs in children, lasts 1–3 months and causes meningoencephalitis and myocarditis, with a death rate of about 8%. Children who survive the acute phase, and infected adults, develop the chronic form of the disease, which may present as a long, symptomless period of latency eventually resulting in either cardiomyopathy or developing as an enteric form involving megaoesophagus and megacolon. Chagas disease is mainly a disease of rural areas and it has been estimated that 16 million people are infected and 25% of the population at risk (Gratz, 1994). There is no specific drug-based therapy and no vaccine. Treatment strategies rely on two approaches: the administration of general anti-parasiticals and the active management of disease symptoms. Prognosis is good if the treatment begins in the first year of the chronic phase for both adults and children. Later treatment results in much poorer outcomes.

The causative organism has been found in a wide range of vertebrates but not all are significant reservoirs. Dogs and cats are major peridomestic reservoirs. Among rodents, and depending on ecological and geographical situations, the guinea pig, *Cavia porcellus*, and the southern plains wood rat, *Neotoma micropus*, are disease reservoirs. In Panama, 57% of roof rats carried *T. cruzi* (Gratz, 1994). Clearly, the complexity of transmission pathways means that rodent control may play only a small part in the management of this disease.

Bacteria

Rodents play a significant epidemiological role in the transmission of a very wide variety of bacterial diseases to humans and livestock (Meerberg *et al*., 2009).

Yersiniosis

Before 1970, little attention given to yersiniosis in the medical literature or in public health. The disease is caused by a bacterium of the genus *Yersinia*, a small Gram-negative bacillus found among wild and farm animals, in water and in sewage. *Y. pseudotuberculosis* and *Y. enterocolitica* have been isolated from wild rats in Japan and the USA, and more recently in the UK (Webster and Macdonald 1995; Battersby *et al.*, 2002). It is said that yersiniosis occurs in all European countries, with the highest prevalence in northern countries and Scandinavia, as well as in Canada, the USA, Australia and Japan. The natural reservoirs of *Y. enterocolitica* are said to include a variety of domestic and wild species, with pigs, rodents, rabbits, sheep, goats, cattle, horses, dogs and cats as prominent hosts. Rats can pass *Yersinia* to humans either directly, or indirectly by the contamination of animal foodstuffs with infected droppings.

A common transmission route is said to be via contaminated milk or water. Direct contact with infected animals may also be a way of transmission. In the Auvergne, France, Gourdon *et al.* (1999) reported the detection of incidents of human cases of *Y. enterocolitica*, with a peak annual incidence of 12 cases during the period 1990–1998. Until 1988, epizootic human infections had been rare in the Auvergne – a cattle-rearing area in central France. The first human case was detected in 1991, and since then the number of human cases of *Yersinia* infection in the region has increased.

Pasteurellosis

Pasteurellosis is caused by *Pasteurella* spp. The causative organism in humans is *P. multocida*, which is commonly transmitted by pet bites. The parasite has not been detected in urban Norway rats in England (Battersby *et al.*, 2002), although it has been detected in rural rats in the UK (Webster and Macdonald, 1995).

Streptobacillus and rat-bite fever

Rat-bite fever (streptobacillary fever) is caused by infection with *Streptobacillus moniliformis*. It is also known as epidemic arthritic erythema (Haverhill fever), and occurs worldwide. It is caused by either the bite of a rat or other infected rodent, or by the ingestion of water or milk contaminated by rats. The incubation period of the disease in humans is 1–4 days. The symptoms include fevers, followed after 2 days or so by a rash, asymmetrical arthralgia (joint pain) and also arthritis. If not appropriately treated, infection may result in endocarditis, myocarditis, meningitis, pneumonia or sepsis, with an untreated mortality rate of 7–13%. *S. moniliformis* is carried in the nasopharynx of the rat and may be excreted in the urine of healthy rats (Battersby *et al.*, 2008). The aetiology of reported outbreaks suggests that Norway rats are important carriers. *S. moniliformis* has been reported in field populations of house mice in Australia (Taylor *et al.*, 1994). In common with many illnesses in which rodents may be implicated, Meerburg *et al.* (2009) pointed out that despite its worldwide distribution, rat-bite fever is rarely diagnosed by physicians.

Leptospirosis

Leptospirosis is one of the most widespread and prevalent zoonoses, particularly in regions of high rainfall. The disease is a complex of different syndromes caused by serovars or serotypes of the subgroup *Leptospira interrogans*. There are more than 250 pathogenic serovars and it is usual to refer to these organisms using a binomial involving the generic name and that of the serovar (e.g. Meerberg *et al.*, 2009). One of the most well-known forms of leptospirosis in humans is Weil's disease, caused by *L. icterohaemorrhagiae*. Weil's disease is an acute febrile disease, the manifestations of which arise from the effects of generalized vasculitis (inflammatory destruction of blood vessels). Rodents, in particular Norway rats, are important reservoirs of infection for humans and domestic animals. Other leptospiral infections are common in tropical areas of the world, but many are also found in temperate areas, including Europe. Infection in humans may follow direct or indirect exposure to an infected animal's urine or to contaminated fresh water; this exposure may be either occupational or recreational. Occupations in which workers operate in wet, rodent-infested environments are particularly prone to infection, such as agricultural workers in rice and sugarcane fields, sewer workers and those in slaughterhouses and fish-processing plants, and on animal husbandry farms. Also at risk are people who work or undertake leisure activities in or around water that might be contaminated with rat urine. The British champion rower Andy Holmes died of leptospirosis in 2010, which he was suspected to have acquired from the water during a race on the River Witham in Lincolnshire, UK.

To initiate the infection, leptospires generally gain entry either through a cut or skin abrasion or through a mucous membrane such as the conjunctiva of the eye. The symptoms are similar to influenza to begin with. However, hepatic and renal pathologies may occur, leading to failure of these organs within 7–10 days if untreated. Leptospirosis is reported as fatal in about 10% of infected humans, with a possible fatality range of 5–40%. This disease has been commonly associated with rats, and Webster and Macdonald (1995) reported the occurrence of *Leptospira* spp. at a rate of 14% in rural rats. According to the Health Protection Agency (HPA), now part of Public Health England, in 2009 and 2010, there were, respectively, 58 and 42 laboratory-confirmed infections in total. The majority of these were indigenous cases, though a significant number of infections were acquired overseas.

Several *Leptospira* strains are directly linked to rodents, such as *L. arborea*, *L. copenhageni*, *L. icterohaemorrhagiae*, *L. bim* and *L. ballum*. Rat-borne leptospires may also cause infection in a wide range of domestic animals, including dogs (*L. icterohaemorrhagiae*, *L. canicola*), cattle (*L. hardjo*), horses (*L. bratislava*), pigs (*L. pomona*) and sheep (several of the serovars previously mentioned and also *L. grippotyphosa*). All these infections may also result in human cross-infection. Leptospirosis is often misdiagnosed or diagnosed nonspecifically as a pyrexia of unknown origin (PUO). The number of human cases worldwide is not well documented (Meerburg *et al.*, 2009), and suffers from consequent underreporting in many areas of the world.

Q fever

Coxiella burnetii is the causal organism for Q (Query) fever in humans. This is a species of rickettsiae that is distributed globally, and it is an obligate intracellular parasite. Morphologically, the genus *Coxiella* is similar to the genus *Rickettsia*, but with some genetic and physiological differences (Meerburg *et al.*, 2009). In 1944, outbreaks of Q fever occurred among British troops stationed in Italy, Greece and Corsica. Q fever is a widespread illness that affects wild and domestic animals as well as man. There are acute and chronic forms of the disease, and there is also another form that presents with influenza-like symptoms. Other symptoms include hepatitis, meningoencephalitis and endocarditis, but these are probably less common. Transmission to humans and animals is normally via aerosols and dust. The organism is extremely stable and resistant to desiccating conditions. Humans acquire infection through inhalation of contaminated dust and contact with contaminated animal products. *C. burnetii* has both a wildlife and a domestic animal cycle. Possible routes of infection from wild animals to domestic animals include contamination of the environment by infected products of conception, ingestion of contaminated grass or ingestion of contaminated animals such as rodents by cats.

C. burnetii antibodies have been detected in the serum of rats in the UK (Webster and Macdonald, 1995; Webster *et al.*, 1995b). Earlier, the only previous report of this organism in wild rats was in India (Yadav *et al.*, 1979). Previously, cattle, sheep, cats and goats were the best-known reservoirs. Norway rats may be significant in the spread of Q fever.

In the USA, low seroprevalences were detected in muskrats, rats (*Rattus* spp.), Beechey ground squirrels (*Otospermophilus beecheyi*), wood rats (*Neotoma fuscipes*), and deer mice (*Peromyscus* spp.) (Riemann *et al.*, 1979). In Japan, another rodent species, *Myocastor coypus*, has shown moderate (13%) seroprevalence for *C. burnetii* (Ejercito *et al.*, 1993).

Salmonellosis

Salmonella is generally regarded as one of the most important food-borne pathogens in the world (Meerburg *et al.*, 2009). Reduction or elimination of these pathogens in the first part of the food chain (i.e. on the farm) is crucial to preventing disease among consumers of animal products. Previous research cited by Meerburg *et al.* (2009) is said to have proved that wild rodents and house mice are able to amplify these pathogens in the environment. Certainly, rats and mice have traditionally been thought to carry *Salmonella* spp. and to be a major reservoir of infection. Nakashima *et al.* (1978) referred to a number of cases where rats had been cited as a source of *Salmonella* and had 'been implicated on numerous occasions as a vector for food-borne salmonellosis' – although that study found little *Salmonella*, and the absence of enteric pathogen was seen as 'striking'. Webster and Macdonald (1995) reported very little prevalence of *Salmonella* spp. in rural rats. There is, then, no real explanation of why rats had been implicated in salmonellosis when most studies that have looked have found few or no isolates in wild rats. However, one study of rats captured in the sewers of Lyon (France) in 1982 did find them to carry *S. typhimurium*, but at a low prevalence of 6%. It has been reported that 8% of fresh Norway rat faecal samples collected in the West Midlands (UK) were positive for *S. enterica* (Hilton *et al.*, 2002) and that viable isolates of the bacterium could be recovered from dried faecal pellets for up to 86 days after they were voided by rats. Firth *et al.* (2014) also found *S. enterica* in 2% of a sample of Norway rats in New York City. As well as carrying the disease in their guts, rodents may also play a part in disease aetiology by mechanical transmission. Therefore, effective rodent control is a recommended procedure to prevent salmonella outbreaks (Meerberg and Kijlstra, 2007).

Campylobacter

This bacterium (with *Salmonella*) is the most important of food-borne pathogens. Many species of *Campylobacter* are capable of causing human pathogenicity, although the main species implicated are *C. jejuni* and, more rarely, *C. coli*. The same species, and others, cause disease in a range of animals, including dogs, poultry and all commercially important species of domesticated stock. In humans, the disease presents with considerable variation, from mild gastric discomfort to acute enteritis with bloody diarrhoea. Outbreaks of *Campylobacter* in young poultry flocks may result in the deaths of the majority of birds, and in bovines, the disease, caused by *C. fetus*, may result in abortion and infertility. Rodents are not a prerequisite for disease transmission though, as faecal–oral transfer may occur. Meerberg and Kijlstra (2007) reviewed the literature and cited many studies in which infection of house mice and Norway rats with *Campylobacter* had been found. A recent study found that 30% of cattle on farms in central southern England were infected with *C. jejuni* (Prescott, personal communication) and rodents on the farms were also infected. As with salmonellosis, rodent control is a requirement in animal-rearing facilities to prevent *Campylobacter* infections.

Escherichia coli

The Shiga toxin-producing *E. coli* (STEC/VTEC – shiga toxin-producing/verocytotoxin-producing) of the O157 serotype can cause a serious human food-borne disease, which can lead to haemorrhagic or watery diarrhoea. In children in particular, this can be accompanied by the life-threatening haemolytic uraemic syndrome, a disorder characterized by thrombocytopenia, anaemia secondary to red blood cell fragmentation and kidney failure. The mortality rate lies between 3 and 17%, and can be up to 30% during outbreaks. In Denmark, wild animals living close to cattle and pig farms were examined for VTEC (Nielsen *et al.*, 2004). Among the 260 samples from wild animals (including birds, rodents and insects) the prevalence of VTEC was generally low. However, VTEC isolates from a starling (*Sturnus vulgaris*) and a Norway rat were identical to cattle isolates from corresponding farms. This study shows that wild birds and rodents may become infected from farm animals, or vice versa, suggesting a possible rodent role in VTEC transmission, but it is unclear what role they might play in the transmission cycle. Firth *et al*. (2014) detected enteropathogenic *E. coli* (EPEC) in 38% of *R. norvegicus* trapped in New York City. Other bacterial pathogens identified in this study were *Bartonella* spp. (25% of rats) and *Streptobacillus moniliformis* (17% of rats).

Viruses

A wide range of viral diseases in which rodents play a part in disease transmission can be found in humans and domesticated animals. For example, Meerburg *et al*. (2009) listed 20 human viral diseases in which rodents have an epidemiological role as either carriers or reservoirs. The aetiologies of many of these diseases are obscure and geographically specific. These viral diseases include Lassa fever, tick-borne encephalitis, equine encephalitis and several rodent-borne haemorrhagic fevers, such as Argentine haemorrhagic fever, Bolivian haemorrhagic fever and Venezuelan haemorrhagic fever. These diseases were addressed in detail in the first edition of this book and will not be covered further here (but see also Table 4.3).

Hantavirus

Viral haemorrhagic fever is a generic term and includes Hantaan fever. A milder but also sometimes fatal disease has also been found in Scandinavia and Eastern Europe that is caused by an antigenic subtype of the Puumala virus. The hantavirus (HTV) is one of the recently discovered aetiological agents of acute viral haemorrhagic fever, which is one of the most well-known viral diseases transmitted to humans from rodents. Meerburg *et al*. (2009) listed 15 different hantaviruses of the Bunyaviridae family, and their rodent carriers/reservoirs.

These rodent-borne viruses cause haemorrhagic fever with renal syndrome (HFRS) and are present globally, although the disease they cause may have different names (e.g. Korean haemorrhagic fever, epidemic haemorrhagic fever and nephropathia epidemica), and may vary in severity depending on the causative virus. HFRS is a major public health problem in China and Korea, where the fatality rate in cases is about 7%.

Hantavirus is the newest described genus in the Bunyaviridae family, and is the only genus in that family that is not arthropod borne, but is transmitted by rodents. Infected rodents remain apparently healthy, but are said probably to have a lifelong capacity to shed infectious HTVs in their excreta. Clement *et al*. (1998) reported indications of the growing importance of the wild rat as a vector for this hitherto unrecognized form of virus on a worldwide scale. Viruses that are serologically indistinguishable from disease-causing hantavirus strains isolated from rats in the Far East have been found in nearly 50% of *R. norvegicus* in residential districts of port cities such as Baltimore (Yanagihara, 1990). Rats trapped from 14 locations in Baltimore were shown to have

Table 4.3. Important viral diseases of humans and animals with rodent reservoirs.

Disease	Geographical distribution	Main rodent reservoirs
Argentine haemorrhagic fever	Argentina	*Calomys*
Bolivian haemorrhagic fever	Bolivia	*Calomys*
Haemorrhagic fever with renal syndrome	Global	*Apodemus*, *Rattus*, *Clethrionomys*
Lassa fever	Africa	*Mastomys natalensis*
Lymphocytic choriomeningitis	USA, Germany	*Mus musculus*
Tick-borne encephalitis (TBE)	Europe, through Russia and Asian republics such as Azerbaijan	*Apodemus*, *Microtus*, *Clethrionomys*
Venezuelan equine encephalitis	North and South America	*Sigmodon*, *Oryzomys*, *Peromyscus*
Venezuelan haemorrhagic fever	Venezuela	*Sigmodon*, *Oryzomys*

antibody to HTV, with antibody prevalence rates higher in residential locations than in parks (Childs *et al*., 1987). Humans are the only known disease end point of the infection.

Hantavirus pulmonary syndrome (HPS) was recognized in the early 1990s in the south-western parts of the USA as an acute disease caused by several related strains of viruses in the genus *Hantavirus*. *Sin Nombre virus* (SNV) (Bunyaviridae) is the hantavirus responsible for HPS in humans, and the deer mouse, *P. maniculatus*, is said to be its primary reservoir in the USA (Mackelprang *et al*., 2001).

Haemorrhagic fever with renal syndrome (HFRS) is characterized by systemic involvement of the capillaries and small vessels, which causes capillary leakage and haemorrhagic manifestations. Renal involvement leading to acute renal dysfunction, as a result of interstitial haemorrhage and interstitial infiltrates, is also common. Approximately 60,000–150,000 cases of HFRS involve hospitalization, with the majority (90%) in China, Russia and Korea.

About half of the rats trapped in Baltimore City had detectable antibody against *Seoul virus*, another HTV. In a sample of 201 rats, antibodies against *Seoul virus* (SEOV) were found in 57.7% – and also *Hepatitis E virus* (HEV), a *Hepevirus*, in 73.5% (Easterbrook *et al*., 2007). Unlike other hantaviruses, SEOV has a global distribution. It is an important aetiological agent in HFRS, but the symptoms are more moderate than those of some of the other hantaviruses, such as the Hantaan serotype (Easterbrook *et al*., 2005). Meerburg *et al*. (2009) reported studies that indicate *R. norvegicus* and *R. rattus* as worldwide spreaders of SEOV. Genetic and serological evidence for the presence of SEOV virus in populations of *R. norvegicus* in Belgium has been reported. Another recent European case also implicated infected Norway rats in the transmission of SEOV to a farmer in Yorkshire, UK, which resulted in acute kidney injury (Jameson *et al*., 2013). In the study of New York Norway rats by Firth *et al*. (2014), SEOV was the only virus detected (in 6%) by specific PCR assays. However using other methods a wide range of known and novel viruses from groups that contain important human pathogens were identified, including sapoviruses, cardioviruses, kobuviruses, parechoviruses, rotaviruses and hepaciviruses.

Other viruses

In north-western Europe, where HFRS is absent (Meerburg *et al*., 2009), there are hantavirus types that cause a mild variant of this disease. Nephropathia epidemica is caused by the *Puumala virus* (PUUV), which is spread by the bank vole (*Myodes glareolus*) in Europe (Sibold *et al*., 1999). There are indications that PUUV can survive for prolonged periods outside the host, which can thus cause indirect transmission via the environment (Kallio *et al*., 2006). About 80% of the infected individuals are asymptomatic or develop only mild symptoms, and the disease does not spread from human to human. Recently, human cases of nephropathia epidemica in Europe due to infection by PUUV have increased (Tersago *et al*., 2008a). It has been found that, besides human activity patterns, local environmental conditions and rodent community structure are also likely to play a role in determining the risk of PUUV infection for humans (Tersago *et al*., 2008b). The grey-sided vole (*M. rufocanus*) has also been associated with PUUV in Japan (Kariwa *et al*., 1995).

Meerburg *et al*. (2009) report other studies in Central and Eastern Europe showing that the yellow-necked field mouse (*A. flavicollis*) and the striped field mouse (*Apodemus agrarius*) distribute two closely related viruses: the *Dobrava-Belgrade* virus (DOBV, also described as DOBV-Af or the Belgrade virus) and the *Saaremaa virus* (SAAV, previously described as DOBV-aa) (Vapalahti *et al*., 2003).

In Korea, the Soochong (SOO) or Amur virus has been found in the Korean field mouse (*Apodemus peninsulae*) and has also been identified in rodents in the north-eastern part of China (Jiang *et al*., 2007).

House mice are known to transmit lymphocytic choriomeningitis (LCM) caused by the *Lymphocytic choriomeningitis virus*, an *Arenavirus* (Lehmann-Grube, 1971). More recently, LCM virus has been isolated from

25% of samples taken from Norway rats on farms in central southern England (Prescott and Stuart, 2011), and with such a high incidence that the chance of human infection is said to be significant. Although LCM is not usually a serious threat to healthy individuals, this viral disease causes severe illness in immunocompromised people and can cause severe birth defects when contracted during pregnancy.

Other studies have found that house mice also carry the *Mouse mammary tumor virus*, which may be linked to breast cancer in people (Stewart *et al.*, 2000).

Conclusion

Rodents play a significant role in the transmission of a large number of diseases to humans and animals, far more than is often appreciated. Our understanding of the role of rodents in many disease aetiologies continues to increase, but much remains to be done. An important constraint is that many of these pathogens cause non-specific and often self-limiting symptoms in humans and animals. Therefore, it is likely that infections with rodent-borne diseases are poorly diagnosed and, to a significant extent, underrecorded. For that reason, it is difficult to establish the true, and probably considerable, risks that they present to public and animal health. What is more certain, however, is that the role played by rodents in human and animal disease transmission is, in many situations, the most compelling reason for the effective management of rodent populations.

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5 Rodent Control Methods: Non-chemical and Non-lethal Chemical, with Special Reference to Food Stores

R.H. Smith[1] and A.N. Meyer[2]
[1]*School of Applied Sciences, University of Huddersfield, Huddersfield, UK;* [2]*Acheta, Chieveley, UK*

Introduction

The most obvious way to deal with a pest that is causing damage is to remove the pest, which usually means killing it. This direct approach may not be either the most effective or the most economic in practice though. For the reasons outlined in Chapter 1, some pest populations may be near to an equilibrium determined by limiting factors in their environment; for equilibrium populations, a reduction in pest numbers and damage will not be sustained unless the killing is kept up. Even for pests characterized by irruptive rather than equilibrium (logistic) population dynamics (see Fig. 1.3, Chapter 1), lethal control alone may not keep up with reproductive output during the build-up of an outbreak. Effective pest control must take account of the temporal dynamics of the pest population.

The main aim of pest management should be to reduce damage, rather than to kill the pest. An immediate pest problem may often require fast results, usually best achieved by use of a lethal chemical (see Chapter 6). Lethal control may, however, be followed by rapid immigration such that the damage reduction is short lived. Equally, exclusion of a pest might prevent damage without recourse to lethal control. Thus, it is also important to take account of the spatial dynamics of the pest. Rodents are mammals with sophisticated behaviour and it is essential to allow for behavioural responses that have evolved by natural selection, thereby increasing individual fitness (Baker *et al.*, 2007).

Environmental Context

Simple ecological theory treats a population as a group of organisms in one place at one time. Numbers (N) change through time according to the numbers of births (B), deaths (D), immigrants (I) and emigrants (E) as illustrated in Fig. 5.1(a). Population size may be regulated if any of the four processes – births, deaths, immigration or emigration – occurs at a rate that depends on population density.

Modern ecology also stresses the role of spatial heterogeneity in population dynamics (Shorrocks and Swingland, 1990). If animals are distributed among patches of environment within which resources are limited but between which there is some migration, then an aggregated distribution of animals among patches can be sufficient to promote population stability under a wide range of conditions. The collection

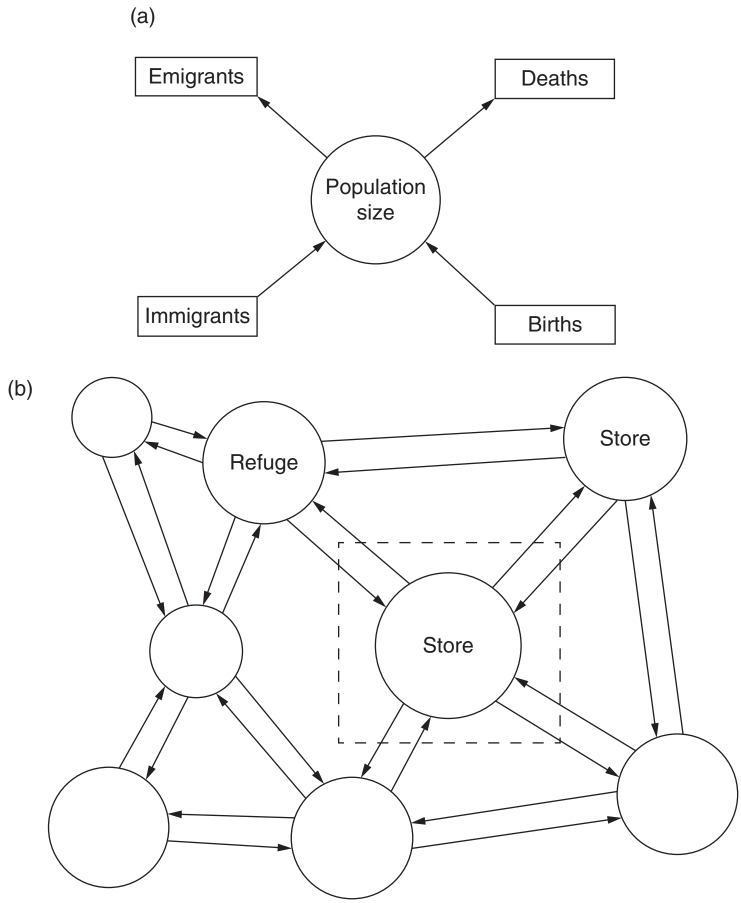

Fig. 5.1. Population dynamics processes. (a) The four processes – births, deaths, immigration and emigration – that can be manipulated to manage a pest population. Conventional chemical control relies entirely on increasing deaths. Any of the four processes may be governed by rates that vary with population density. (b) The metapopulation concept. The dynamics of the pest population may depend on migration between local populations in patches of suitable habitat as much as on within-patch dynamics. Exclusion effectively isolates a patch (e.g. a grain store) from the metapopulation.

of local populations in patches linked by migration may form what is known as a metapopulation (Fig. 5.1b). Human activity often leads to patchily distributed resources that may be exploited by a metapopulation of rodents (e.g. a mosaic of agricultural crops). Patches vary in resource quality in time as well as space and, in consequence, a high average metapopulation density may be maintained. Not all of the patches occupied by rodents may be of direct interest (some may be non-crop areas, others may belong to neighbours), but their role in rodent population dynamics, and hence rodent damage, cannot be ignored. Clearly, exclusion of rodents from a patch ($I = 0$) will prevent damage. Any environmental manipulation that reduces rates of migration may destabilize pest population dynamics and, perhaps in combination with manipulation of births or deaths, could effectively control the damage without killing rodents directly.

Within the context of manipulating rodent numbers in both space and time, the main options available will now be reviewed.

Preventing and Reducing Immigration

Exclusion of rodents from a commodity or structure at risk can take many forms, and could be very local to the item to be protected (e.g. a tree guard) or a barrier to entry to a large area (e.g. an electric fence). The essential feature of exclusion is that it must take account of both the physical ability and the biology of the potential pest species. Thus, the roof rat, *Rattus rattus*, is a better climber than the Norway rat, *Rattus norvegicus*, and is therefore less easily excluded from buildings with high-level apertures. The Norway rat, in contrast, regularly burrows 30 cm below ground, though it may go deeper (Pisano and Storer, 1948), and so building foundations or other below-ground barriers should take account of this and go down at least 45 cm (Greaves, 1982). The Norway rat is also sufficiently powerful to jump 75 cm vertically and to scramble higher if it can achieve any purchase. In general, rodents can squeeze through any aperture that their heads will go through as their bodies are very flexible. Consequently, rodent-proof structures must have apertures no larger than the smallest rodent pest that might attempt to enter, which is as small as 6 mm in the case of the house mouse, *Mus domesticus*. Complete exclusion may be expensive, and a good level of reduction of immigration may be more cost-effective. Some examples are described later in the section on Proofing under 'Case Study: Food Stores'.

Rodent proofing premises

The essential features of adequate proofing are as follows:

1. Materials must be resistant to gnawing, e.g. brick, concrete blocks, sheet metal (preferably galvanized steel), fine-mesh metal.
2. Apertures should be 6 mm maximum.
3. Climbing guards must be sufficiently high up drainpipes, etc., to prevent animals jumping beyond them and wide enough to prevent the animals climbing around them.
4. Drain traps will prevent access through drains and sewers.
5. Doors must be kept closed and free of debris.

Fuller details can be found in Jenson (1979) and in the section 'Case Study: Food Stores' later in this chapter.

Barrier methods

Barriers on individual crop plants are only viable for large, long-lived plants, such as coconut or oil palms, where damage may affect the long-term as well as the immediate yield. Sheet metal to an appropriate height (90 cm) can prevent rats gaining access, but exposed edges may provide a means of climbing, especially for the agile roof rat.

Whole plots of rice have been protected by barriers in the Philippines (Quick and Manaligod, 1990). It is very costly to make a barrier absolutely rodent proof, but in the case of high-value crops (e.g. experimental variety plots), the cost may be worthwhile. One survey of barrier methods used to protect experimental rice plots at the International Rice Research Institute (IRRI) in the Philippines, however, showed little evidence of their cost-effectiveness (Ahmed *et al.*, 1987). Barriers should be particularly cost-effective if they provide a high level of relative, if not absolute, protection and are surrounded by areas with easy access to food and shelter that the rodents find more attractive. This, again, highlights the importance of spatial scale – an imperfect barrier could be quite effective if the rodents can choose to take an option of easier access, but not if the rodents cannot easily forage elsewhere.

We can regard some aspects of habitat manipulation as a barrier method. Most species of rodent are unwilling to cross open areas such as tarmac roads (Wilkins, 1982), and it is well known that rodent infestations can be effectively discouraged if a *cordon sanitaire* of ground clear of weeds and any possible harbourage is maintained around a building.

Finally, we note that barrier methods linked with trapping have been developed in the trap-barrier system (TBS), which is described in detail in Chapter 3 (see Singleton *et al*., 1999).

Electric fences

The literature on non-lethal electric fencing as a barrier method has been reviewed by McKillop and Sibly (1988), and Schumake *et al*. (1979) evaluated non-lethal electric barriers for protecting crops from rodents. Lethal electric shock has been used against rodents in the Philippines (Quick and Manaligod, 1990). Untransformed mains electricity has also been used, but this method is highly dangerous and cannot be recommended. The main problem with lethal electric fences, apart from human safety, is that they are often rendered ineffective by the first rodent killed, which may short-circuit the wires. Conditioned avoidance of non-lethal electric fences has proved cost-effective against rabbits, *Oryctolagus cuniculus*, as crop pests in the UK (McKillop and Sibly, 1988). Electric barriers may be feasible in some circumstances, though as with all methods they must be compared with the efficacy, cost-effectiveness and acceptability of alternatives.

Diversion feeding

There are a few circumstances where it may be cost-effective to exclude a pest from a crop by providing alternative food as a diversion. Diversion feeding has been used successfully in Germany to prevent the consumption of sugarbeet seeds by the wood mouse, *Apodemus sylvaticus* (Pelz, 1989). Damage only occurs in newly sown sugarbeet fields in years when other high-energy food (invertebrates, cereals) is scarce. The occurrence of damage can be predicted quite well from rainfall, and cereal seed is provided as a diversionary food after sowing if there is likely to be a wood mouse problem. This can be thought of as a sort of behavioural exclusion, but it is only feasible where damage is infrequent and predictable, conventional control is either uneconomical or unacceptable, and the commodity protected has sufficiently high value. In the case of sugarbeet in Europe, the main cost of damage is the cost of replanting (labour and machinery) rather than the seed itself.

Ultrasound and electromagnetic devices

The sense of hearing of rodents extends well into the ultrasonic range (i.e. above 20 kHz); for example, in Norway rats it extends up to 100 kHz, with most response around 40 kHz, and in house mice it extends up to 90 kHz. Ultrasound production in rodents is associated with various behaviours, including reproductive and aggressive behaviour, and high-frequency sounds at very high intensity can kill house mice (through overheating). In consequence, a number of ultrasound devices have been marketed, mostly for use in buildings. Meehan (1984) and Lund (1988) reviewed the evidence on the efficacy of ultrasound devices as deterrents to rodent immigration and concluded that there is no convincing evidence that any of the machines available is effective. Interestingly, many consumers seem willing to pay substantial sums of money for electronic gadgets when they are unwilling to take cheaper, more effective measures such as proofing and hygiene. Lund (1988) reported estimated expenditure on ultrasonics of US$17 million in 1982 in the USA alone. If ultrasonic devices are to be effective in future, however, they must overcome the drawbacks listed in Table 5.1. There has also been interest in units that produce an electromagnetic field to exclude rats and mice, but Fitzwater (1978) found little scientific support for their effectiveness in pest control.

Chemical repellents

We are currently unaware of any effective chemical repellent available that is not also toxic (Meehan, 1984). An important requirement of a repellent is that it should repel by olfaction rather than taste, or else some damage to a commodity or structure will occur during

Table 5.1. Drawbacks of ultrasonic devices in relation to their effectiveness in rodent control. Some of these problems might be overcome by future technological developments, while others are probably insuperable (because of the laws of physics).

Applicability	Restricted to areas close to power supplies, i.e. buildings
Attenuation	Ultrasound is readily absorbed by solid materials
Cost-effectiveness	At present, does not compare with conventional methods
Directionality	High-frequency sounds do not reflect around solid objects
Habituation	Initial aversion by rats and mice is rapidly overcome
Intensity	Effective ultrasound intensities may be harmful to man

tasting. Research biologists are often attracted by the concept of using pheromones or other chemicals that communicate a response other than simple distaste. Stoddart (1988) reviewed potential pheromone manipulations. In theory, such chemicals could protect large spaces because only small numbers of molecules of a pheromone are needed to elicit a response. In practice, like all methods that do not exclude absolutely, behavioural manipulation is only effective if the animal can choose a more attractive alternative. When food or harbourage is short, or population density is high, methods that do not exclude absolutely may be overcome if the animal perceives that the alternatives are worse in terms of potential for survival or reproduction.

Emigration

Methods for reducing population density to an acceptable level by persuading rodents to emigrate overlap considerably with some of the methods described above that prevent or reduce immigration. Animals migrate out of an area for a number of reasons:

- to find food;
- to find a mate or a place to reproduce;
- to avoid natural enemies; and
- to find a more comfortable environment.

Apart from introducing natural enemies (described below), rodents can most easily be made to feel uncomfortable by removing food, water and shelter. Habitat manipulation around field crops includes clear cultivation following harvesting of a crop, the elimination of shrubs and herbaceous plants around fields and orchards, reduction of the bund/paddy ratio in rice, and synchronization of planting and harvesting (Fitzwater, 1988). In buildings and stores, the equivalent procedures are hygiene and sanitation (see later section 'Case Study: Food Stores').

There are a few physical control measures that can cause rodents to emigrate, for example flooding burrows, or poking squirrel dreys, although these are probably carried out primarily in order to kill rodents. Ultrasonic methods, repellents and diversion feeding might also be used in order to persuade rodents to emigrate as much as to deter immigration. However, in practice, a resident infestation is more likely to be treated using a lethal method.

Reduction of Pest Birth Rate

If population dynamics represented a steady-state system comparable to simple chemical reactions, reducing pest birth rate would decrease the 'standing crop' population of pests (Fig. 5.1a). In equilibrium populations, though (Chapter 1), there are non-linear terms in the equations describing the population dynamics that may lead to compensation for changes in population density (Sinclair, 1989). Thus, reducing the birth rate may result in, for example, a compensatory reduction in the natural death rate or an increase in immigration, especially in species that hold individual or group territories (see Chapter 1) in which a vacant territory space is soon filled. With this proviso, there are various possibilities for reducing the birth rate of the pests, which are outlined here.

Removal of nesting opportunities

Clean farming practices and sanitation measures that reduce immigration will also remove nesting opportunities, or at least make potential nesting sites less attractive. In buildings and stores, building design can play a large part. For example, insulated cavities that are widely used in animal units in temperate climates to reduce heat loss can provide ideal nest sites for rodents unless the building construction prevents access to them.

Disruption of reproductive behaviour

The 'Bruce effect' in house mice shows the potential for disruption of reproduction by odours (Bruce, 1960); this phenomenon is when the presence, or even odours, of a strange male in a population may disrupt the female reproductive cycle or even cause pregnant females to abort. Stoddart (1988) considers that the conditions under which the Bruce effect is observed in the laboratory are not relevant to wild populations and that the phenomenon is unlikely to have any practical application. The Bruce effect has been observed in other mice and voles, but not in rats (Meehan, 1984).

In theory, ultrasonic devices could disrupt reproductive behaviour even if they fail to drive rodents away (see section on 'Preventing and Reducing Immigration' above). In practice, rats and mice habituate to ultrasound, and in any case, high-frequency sounds do not readily penetrate to rodent burrows and nests.

Reproduction is probably most likely to be affected by nutrition. Many plants produce chemicals of the steroid type that can prevent ovulation (see below), but nutritional status is the main determinant of reproductive output in many species. In East Africa, the role of rainfall and vegetation succession in the population dynamics of species such as the multimammate rat, *Mastomys natalensis*, has been well studied (e.g. Leirs, 1992), and in theory reproduction could be minimized if high-quality food (seeds, etc.) was not allowed to mature, e.g. by using herbicides. In practice, this sort of manipulation is neither possible nor ecologically acceptable on a large scale. In contrast, in animal production units, the obvious precaution of clearing up and preventing access to high-quality feed concentrate will keep down reproductive output as well as reduce immediate losses.

Finally, we should note that female rodents will not reproduce without males. Although there are few occasions when fertile males are in short supply, the successful campaign to eradicate the coypu, *Myocastor coypus*, in eastern England seems to have been in part because rarity of males limited population fecundity (Gosling and Baker, 1989). This example is discussed in the section on trapping as a means of increasing pest death rate.

Reproductive inhibitors

Chemical inhibitors of reproduction can target either the male or the female. Application will invariably be oral (but see immunosterilants below), and the problem of persuading enough animals to consume enough bait arises just as it does for conventional chemical control (see Chapter 6).

Oestrogenic steroids were tested against rodents following their development for the contraceptive pill for humans. Two early field studies against Norway rats were carried out by Brooks and Bowermann (1971) and Kendle *et al.* (1973), and Marsh (1988) lists more recent studies. One synthetic oestrogen (BDH 10131) achieved very promising results (Kendle *et al.*, 1973) because a single exposure to bait made female rats infertile for almost a year. There are, however, problems of palatability and cost with these compounds. Rowe and Lazarus (1974a,b) found that efficacy (measured by prolonged suppression of reproduction) was increased if rats were fed plain prebait (see Chapter 6) before BDH 10131 was applied. Jacob *et al.* (2008) describe more recent research on fertility control of rodent pests and concluded that there is a need to make techniques *specific* to the pest and *deliverable* by bait.

The principles of population control by the use of gametocides were outlined 50 years ago by Davis (1961). The only male antifertility compound to have been widely marketed is alphachlorohydrin (Epibloc®).

The problem with male sterilization is that, in polygynous species, a high proportion of males must be treated to have any effect on population fecundity. Alphachlorohydrin has variable effects in different species (Marsh, 1988), and is also toxic at higher doses, causing up to 50% mortality. Ericsson (1982) has extolled the virtues of alphachlorohydrin as a toxicant–sterilant, though it has not made a major impact in rodent control. There is little doubt that a whole lot of other male antifertility compounds, developed for use in humans, maybe rejected for safety reasons, could have potential for rodent control, but companies seem to have little interest in their development. In part, this is because of the feeling that they are not sufficiently effective, and that the customers will not be happy to have any live rats around, sterile or not. The balance of prejudice could change as public attitudes become ‘greener’ and lethal chemical control becomes less acceptable, although the costs of registration of chemosterilants may prove to be too high. Smith and Greaves (1987) suggested that male chemosterilants could have a role to play in the management of anticoagulant resistance (see Chapter 9) by sterilizing resistant survivors of anticoagulant treatments, and Marsh (1988) discusses the use of chemosterilants in integrated programmes alongside conventional rodenticides.

Biological sterilants

Singleton and Redhead (1991) outlined two approaches to the biological control of fertility in rodents. In the CSIRO (Commonwealth Scientific and Industrial Research Organisation) Division of Wildlife and Ecology in Australia, the hepatic nematode *Capillaria hepatica* in house mice was found to reduce the number of litters produced and young weaned over 3 months. This chronic effect of the parasite appeared to be sufficient to regulate mouse populations below plague levels (the house mouse is irruptive in Australia). The potential for biocontrol by *C. hepatica* was, however, not borne out by large-scale field experiments (Singleton *et al.*, 1995).

A further development at CSIRO was the initiation of projects on the control of fertility in various mammals, including mice, using immunosterilants that might be delivered by a virus vector (Singleton and Redhead, 1991). The potential of this interesting approach was based on developments in genetic manipulation and has been reviewed by Chambers *et al.* (1999), albeit there was widespread concern about whether the technique presented an environmental hazard, and this seems to have curtailed further development.

Overview

Reproductive management is an approach that has potential but remains to be proven as an effective means of control that is comparable with the use of chemical rodenticides. The concepts underlying the approach are subtle and need to be marketed with sensitivity to potential users. The emphasis is on population management rather than simple pest control, and an understanding of the ecology, population regulation and social behaviour of the pest is necessary, even though this is also true (but often ignored) in relation to conventional lethal control. Reproductive management is unlikely to be of much use in food-processing premises or human habitations, where there is normally a nil tolerance of rodents and their signs. In such circumstances, exclusion and lethal control will continue to be the main methods used. In contrast, in agriculture and forestry, where a few rodents are acceptable but the large-scale application of chemical rodenticides may become unacceptable, there is a potential for reproductive management, while noting that natural processes of population regulation need to be taken into account as well.

Increase Pest Death Rate

Non-chemical lethal methods may be carried out in order to eliminate a pest population, or to reduce population density to a level where damage is acceptably low. Trapping and hunting must be the oldest methods of rodent control, and deliberate biological control by keeping cats in grain stores goes back thousands of years, yet these methods are largely discounted by pest-control practitioners. So, how useful are these non-chemical lethal methods?

Trapping and hunting

The main practical problem with trapping and hunting methods is that they are labour intensive and therefore unlikely to be cost-effective in countries where labour costs are relatively high compared with the cost of chemical rodenticides. However, there are circumstances where trapping usefully supports conventional chemical control, or can replace chemical control in areas of high risk or environmental sensitivity.

There are many types of trap, but they nearly all have the same drawback: there is a limit on the number of rodents that can be trapped (usually one per trap), and so they need regular attention. Greaves (1982) recommends that the number of traps used should be two to three times the estimated numbers of rodents present! As a means of lethal control, then, traps have strictly limited value, except in the following special circumstances:

- removal of a small number of rodents in food stores or domestic premises;
- use of sticky traps or glue boards in buildings where other methods are ineffective (e.g. extreme neophobia) – a method that is generally considered to be inhumane;
- where the carcasses are valued as food; and
- control of a small population of large rodents, e.g. coypus.

Active hunting methods are probably even less cost-effective than trapping. Sometimes, opportunistic hunting may not cost much (though it probably has little effect on the pest population). In countries where rat drives are carried out around harvest (e.g. Thailand), the benefits are probably mostly social or nutritional (a rat barbecue) rather than financial (damage reduction). Equally, shooting rodents such as squirrels is only worthwhile for recreation or food, unless the numbers involved are very small. Bounty schemes have been introduced to encourage hunting, but they are usually ineffective and open to abuse (rodents are harvested or farmed rather than eliminated; Greaves, 1982).

The best example of a successful rodent-control campaign based on trapping/hunting is that of the coypu in eastern England (Gosling and Baker, 1989). The coypu was introduced from South America to fur farms in the UK, but some escaped and formed feral populations in the wetlands of eastern England during the 1930s. Apart from damage to crops in an area where high-value vegetables are grown, the coypus caused considerable structural damage to the banks of dykes and watercourses, and also damage to the indigenous vegetation in one of the few substantial wetland areas of Britain. A concerted control campaign was initiated by the former UK Ministry of Agriculture, Fisheries and Food (MAFF) in 1962, and the main method of control has been live trapping on floating rafts followed by humane euthanasia. During the 1980s, the campaign was intensified by the employment of more coypu trappers working in designated areas. An unusual bounty system was introduced whereby the trappers were to be paid a substantial terminal bonus if the pest was eradicated within a certain period of time; thus, unlike most bounty systems, there was a real incentive to eradicate rather than to ranch and harvest. Further details can be found in Gosling and Baker (1987).

As noted above, the success of the campaign was in part due to the shortage of mates for the females as the population density declined. Male coypus range more widely than females and are more likely to be trapped, with the consequence that the sex ratio became more female biased and fecundity declined (Gosling and Baker, 1989). Although the coypu example is a rather special case, it does demonstrate how effective organization linked to the population biology of the pest can achieve the desired result.

Biological control: parasites and diseases

Until the late 1970s, it was generally considered that parasites and diseases had a sporadic effect on animal populations, causing occasional epidemics, but playing no role in population regulation. A series of experimental and field studies stimulated largely by the theoretical work of Anderson and May (1978, for example) has changed our views. Because parasites are distributed in a non-uniform way between hosts, and because the debilitating effects of parasites and the transmission of parasites between hosts depend on parasite load, parasites can have a regulatory role in their host population dynamics. The exploitation of these ideas in relation to the hepatic nematode, *C. hepatica*, and the house mouse has already been mentioned (Singleton and Redhead, 1991); as well as affecting host birth rate, parasites may also affect death rate, not necessarily through causing mortality directly but through a debilitating effect that renders the host vulnerable to other sources of mortality.

Of course, the best-known example of pest control by a disease agent is that of myxomatosis and the rabbit (a lagomorph, closely related to rodents). The introduction of the myxoma virus from South America to Western Europe had a dramatic effect on rabbit populations in countries such as Britain where it was a major agricultural pest. The rabbit population was reduced to a fraction of a per cent of its previous level in Britain. Coevolution involving increased tolerance in the rabbit and decreased virulence in the myxoma virus has allowed rabbit populations to build up again, but the timescale over which this coevolution has occurred is much longer than that for the evolution of anticoagulant resistance in rats (see Chapter 9). No similar disease has been found to keep a rodent pest in check. *Salmonella* bacteria were extensively used against rats in Europe earlier in the 20th century, but the serotypes used were not specific to rats and caused outbreaks of gastroenteritis in human populations (see Meehan, 1984, for a review). Genetic engineering might well provide a species-specific pathogen, but specificity would reduce the commercial value (as with the chemical rodenticide, Norbormide) and make the development and registration costs prohibitively expensive in relation to potential sales. A pathogen that was not completely specific to rodents but not dangerous to other species could be ideal; for example, one that could be cleared from the stomach by vomiting in non-target species could be viable because rodents are unable to vomit.

Biological control: predators

Newsome (1990) has reviewed whether vertebrate pests can be controlled by vertebrate predators, even though conventional wisdom is that vertebrates are normally a poor prospect as biological control agents (Greathead and Waage, 1983). Examples of deliberate introductions of predators have often resulted in the predator becoming a pest, e.g. an introduction of the barn owl, *Tyto alba*, to control rats in a small island in the Seychelles (Blackman, 1965, cited by Duckett, 1991). In other cases, such as the feral cat, *Felis felis*, the predator seems to regulate mice and roof rats in New Zealand forests (see references in Newsome, 1990), though all three introduced species have had adverse effects on the native fauna.

One of the theoretical problems with using vertebrate predators as biological control agents is that their generation time is usually substantially longer than that of their prey and therefore the numerical response of predator populations is insufficient to keep up with rapidly changing prey populations. In reality (except on small islands with impoverished fauna), predators feed on a variety of prey species and switch their attention from one to the other according to their relative abundance. This switching behaviour has two important effects: it allows the predator to survive when a particular prey species is low in numbers; and it helps to keep in check irruptive increases of prey. Predator species that are able to respond to variations in prey numbers in space as well as in time are likely to be of the most use in biological control and, for this reason, predatory birds may be potentially more valuable than mammals.

One of the most interesting examples of apparently successful rodent control by a vertebrate predator is that of the barn owl and the wood rat, *Rattus tiomanicus*, in Malaysian oil palm plantations. Following the introduction of oil palm to Malaysia from West Africa, various rodent species exploited the new resource and the most important pest now is the (Malaysian) wood rat. Barn owls, previously known only as migrants from Indonesia, spread along with oil palm, eating little else but wood rats (Lenton, 1980). However, although the potential of the barn owl as a biological control agent was recognized (Lenton, 1980; Wood, 1985), a shortage of nest sites limited the population growth of barn owls (Lenton, 1980; Duckett, 1991).

In 1987, a 1000 ha field trial was set up with artificial nest boxes at a density of one per 5 ha, and boxes were inspected monthly for 29 months (Duckett, 1991). The increase in nest box occupancy (from 22 to 35% in the first 12 months, rising to 68%) and in numbers of young owls reared was associated with a decrease in loss of oil palm yield due to wood rat damage from a typical 6 to 1.5–3.9%. The calculated payback period for nest boxes was only 2.5 years, and the nest box scheme seems to have been very successful (though lack of replication is always a problem with evaluating large-scale trials of this type).

How could this system work when the barn owl feeds almost entirely on the wood rat yet the generation times are so different? The answer almost certainly lies with the spatial dynamics of the predator. Residents of nest boxes defend their territory close to the nest site, but non-breeding juveniles are tolerated in the intervening spaces. The non-breeders seem to mop up the rats when rat numbers are high, but disperse when there are fewer rats (J.E. Duckett, personal communication). Thus, the movement of owls into and out of the 1000 ha plot allows a density-dependent spatial (rather than numerical) response to rat population density. The success of the scheme, then, seems to depend on the scale of the operation in relation to the dispersal distance that the predator can achieve. If all the plantations in a very large area had a high-density grid of nest boxes, compensatory migration would not be possible and owl reproduction might not keep up with the rats. Hence, biological control schemes of this sort may work best if only a few people use them!

Case Study: Food Stores

Broadly, rodent populations require three main requisites to survive: food, water and harbourage. The more abundant the availability of these key factors, the more likely it is that the population will thrive. Although a shortage of any of these key factors can limit the population, it is most commonly the availability of food that is found to be the limiting factor, either because it is not available in sufficient quantity, or because it is not available on a consistent basis and its availability changes on a seasonal or other less predictable basis. Food stores frequently, but not always, overcome this limiting factor by providing food on a consistent and non-restrictive basis. In drier, arid areas, the availability of water rather than food may be limiting. In general, however, rodent populations are able to adapt to surviving in situations of low water availability. Water is in any case frequently available in storage situations, if for no other reason than that it is required by those who work at the site or by the animals that are kept there.

The availability of harbourage is less frequently limiting because rodents are able, through their adaptability, to take advantage of a range of environmental situations, utilizing both the horizontal and vertical components of their environment; their mobility in this respect enables them to take advantage of marginal harbourage resources. In the absence of obvious harbourage, rodents are also able to create their own, either by burrowing or by gnawing into otherwise inaccessible areas. They are, in addition, able to collect available materials together to create a suitable nesting or resting environment. Food stores and animal production units, therefore, with their provision of a relatively unlimited supply of the factors most commonly limiting population growth, provide an ideal situation in which a rodent population can develop and expand.

Losses

The problems caused by rodents in stores are wide ranging. Attempts to quantify losses inevitably fail to do anything but confirm the variability of the problem and the difficulty of measuring losses caused by mobile species in dynamic environments. Broadly, losses may be attributed to the following:

- direct consumption of food;
- food contamination and damage;
- structural damage;
- disease transmission;
- source of reinfestation of adjoining areas; and
- costs associated with control operations.

These are discussed below.

Direct consumption of food

Rodents eat food intended directly for human consumption or for consumption by domesticated livestock. The impact of direct consumption may be relatively limited in developed countries, but can be a major problem in countries where food is scarce and alternative supplies may not be found in time to prevent hardship for the human population. On average, rodents need to consume about 10% of their body weight each day, but consumption will vary with the size and species of rodent, and with the prevailing climatic conditions. Adult Norway rats can be assumed to eat, on average, about 30 g of dry food a day. A population of 100 adults would, therefore, consume just over 1 t of dry food a year.

Although it is relatively easy to estimate the theoretical food consumption of a rodent population, the actual consumption of a population of rodents is difficult to estimate with any degree of precision.

Damage and contamination of food

Rodents damage and contaminate far more food than they consume. Through their gnawing activity, they damage the sacking, packaging and storage facilities used to store and transport the food. Food is lost through spillage and wastage, and is also thrown away as unsuitable for human consumption. Even though this food is not consumed by the rodents it is, nevertheless, made unavailable for human and livestock consumption and so is effectively lost (Hunter, 1980).

Rodents contaminate food principally through their droppings, hair and urine. Commensal rat species like *R. rattus* and *R. norvegicus* produce about 40 droppings a day each; thus, a relatively small infestation of ten rats would produce some 146,000 droppings a year. If only a few of these find their way into the food intended for human consumption there is a chance that the food will be rejected as unsuitable and its value will be significantly reduced. Urine is far more difficult to detect, but the same rat infestation will produce some 54 l of urine over the year. Not surprisingly, rodent-contaminated food is shunned by processors and consumers (Gecan *et al.*, 1980).

Estimates of stored food losses vary considerably (Hopf *et al.*, 1976) and are dependent on commodity, site and the way in which the calculations of loss are made. In general, though, losses are greatest in tropical and subtropical countries, reflecting not only a more extensive rodent problem but also less sophisticated storage techniques. Estimates range from losses of zero or a fraction of a per cent to as high as 50% or more in some situations. Many estimates lie in the range 1–10% and invariably include total losses due to consumption as well as spillage, damage and contamination resulting from rodent activity. Any reduction in this level of loss on a local, national or international basis clearly has the potential to release significant additional quantities of food for human and livestock consumption. On a worldwide basis, it was estimated by Brooks and Rowe (1979) that some 33 million t of cereals in storage are lost to rodents every year.

Reliable figures on the relative losses due to direct food consumption by rodents and indirect losses due to spillage and contamination are not available. Some estimates are that up to ten times as much food is lost as a result of spillage and contamination as is lost to direct rodent consumption. Loss due to spillage and contamination probably contributes the majority of the loss, but the exact proportions are not important.

Barnett (1951) found that small enclosed populations of *R. norvegicus* (10–26 rats), each with access to 1 t of sacked wheat for 12–28 weeks, caused a loss in weight of 4.4% of the wheat. However, 70.4% of the wheat was fouled and had to be cleaned before use. The main monetary loss at that time was the cost of damaged sacks. The total monetary loss was 18.23% of the original value of the wheat and sacks.

While estimates of financial loss are valuable, perhaps the most immediate impact locally is to estimate the number of rodents that would eat the same as an adult human being. Inevitably, estimates are approximate and vary, but assuming daily adult human mixed dietary requirement of 600 g then about 20 *R. norvegicus* will eat the same amount of food as a human being. If estimates relating to spillage, contamination and spoilage are also correct, then it only takes a very few rats to remove or make unavailable the food required to feed a human being for a day. In areas of high rodent infestation and restricted food availability, this reduction may be critical.

Structural damage

Food is not the only material that is susceptible to rodent gnawing and activity. Sacking, packaging and building structures are damaged and will be costly to repair or replace. Damage to roofing, walls, insulation, foundations and doors of buildings reduces the efficiency and security of the storage facility. Damage to a roof allows water to enter the building, whereas damage to walls, doors, foundations and floors not only weakens the structure of the facility, but also increases the likelihood of further infestation of the facility, allowing in more rodents and frequently increasing the level of rodent damage. Effective control of insect pests by fumigation is also prevented if a structure is not gas tight.

The electrical system is the single most susceptible component of a storage facility to rodent damage. Most stores depend upon electricity for light, heat, air conditioning, ventilation, feed supply (in the case of animal units) and general management. If this electrical system is damaged and the power supply lost, then not only does the facility cease to function, but there is potential for consequential damage to and loss of the commodity that is being stored. Ventilation in large grain stores in the humid tropics, ventilation and heat in intensive poultry units, and grain-drying facilities in major grain stores, all depend upon the regular supply of electricity. At the extreme, fire due to rodent damage to electrical wiring can cause complete loss of the entire facility and all its contents.

Reliable estimates of loss are not available, but in one case known to the authors in the UK, an intensive egg-production facility comprising eight production units on one site employs an electrician full time on a 24 h/7 day call to repair electrical faults due to house mouse damage. Few days pass without one or more calls to repair electrical faults caused by mouse damage.

Rodent-borne diseases

Rodent infestations present a health hazard wherever they are. The nature of the hazard and severity of the risk will vary with the species of rodent and the geographical position. A comprehensive summary of the role of rodents as carriers of disease is contained in Chapter 4.

It should be remembered that rodents not only present a health hazard to people working in a store but also to any animals contained within it. If the storage facility is being used for livestock production then the livestock will also be at risk from diseases transmitted by rodents, particularly where both the livestock *and* the rodents are found at high densities. Work by Opitz *et al*. (1991) on the epidemiology of *Salmonella enteritidis* has identified the rodents as being the most significant amplifier of environmental contamination in poultry houses.

Source of infestation

By their very nature, stores present the potential to support significant rodent populations from which some rodent emigration will take place. Where the units are situated close to human habitation or field crop production, the potential exists for the transmission of disease and field crop damage. The control of peripheral infestations is unlikely to be effective while the focus of the infestation remains. Conversely, of course, these peripheral sites may have been the source of the original infestation.

Costs of control

The costs of maintaining a rodent-free storage environment must be borne in mind when discussing the total costs of rodent infestation. In the UK, farmers are often required to pay for rodent monitoring and prophylactic control in order to satisfy the requirements of their main market (supermarkets). The costs and benefits of undertaking control are discussed later in this chapter.

The approach to the control of all these species is broadly similar and is based on the development of a comprehensive rodent-control strategy that should take account of all the variables that may be encountered. The remainder of this chapter will be concerned with the development and application of this rodent-control strategy.

Developing rodent-control strategies in food stores

A rodent-control strategy is simply the plan that will most efficiently and effectively enable a particular storage facility or group of storage facilities to be kept free of rodents. To be effective, the plan should define strict objectives, and then identify clearly the step-by-step approach required to achieve these objectives. The strategy must include a method of monitoring so that progress towards the objectives can be identified.

It is unusual to find a storage facility anywhere in the world in which a rodent problem of any significance exists and in which no control measures have been taken. Why then do the rodent infestations so frequently persist and why do the amounts of loss, contamination and damage continue at levels of up to 10%, and sometimes higher?

Part of the problem certainly is the perceived high cost of applying some of the more recently developed rodenticides, resulting in reliance on less effective techniques. As will be shown later, this perception is frequently incorrect, and the benefits of applying effective, but perhaps more costly, control over cheaper but less effective techniques greatly exceed costs. The major cause of failure, however, is failure to appreciate that effective long-term rodent control has to be supported and directed by a sound infrastructure. Essentially, this means that the appropriate management structure should be in place and that staff should be trained. Only then will it be possible to utilize the most appropriate control techniques effectively.

Management

Control failure is often caused by the absence of clear management responsibility and correct management decisions. The first step in any strategy is to develop a clear line of command that will be responsible for both developing and implementing the strategy, and for failure if the strategy does not meet the objectives that have been set. The areas and scope of responsibility of this management system should be clearly defined.

Only when the management structure has been put in place and responsibilities defined is there any point in starting to develop a detailed rodent-control strategy.

Training

Training to an appropriate standard is essential. The first step will be to ensure that the managers responsible for developing the strategy are fully trained, not only in management techniques, but also in the essential practical techniques applied by those they manage. Formal academic training, field training and visits to comparable facilities/organizations will be necessary.

The managers must then ensure that all of their staff are trained to the standard appropriate to their intended role and that the training is maintained over the life of any long-term strategy. Training courses and their design need to be carefully considered and must take account of the role that the trainees are to fulfil. All training should cover certain basic features:

- reasons why rodent control is necessary;
- rodent biology and reproduction;
- rodent behaviour relevant to control operations;
- surveying an infestation;
- store and animal unit design and structure;
- use of rodenticides and rodenticide formulations;
- rodenticide toxicity;
- safe use of rodenticides;
- other methods of controlling rodents; and
- problems encountered in control, including rodenticide resistance.

Implementation

Once managerial expertise has been developed and staff are trained, then details of the rodent-control strategy can be considered. Any strategy should take account of the following points:

- survey;
- application of control techniques;
- maintenance;
- hygiene;
- proofing; and
- monitoring.

These are discussed below.

SURVEY. The objective of the survey is to identify the severity and extent of any rodent infestation before any control techniques are applied. The most common cause of failure of subsequent control operations is underestimation of the extent of an infestation.

As rodents are largely nocturnal, the surveyor will have to use signs and traces such as droppings, runs, holes, etc., to identify the species present and the extent and severity of the infestation. All areas should be surveyed both inside and around the facility. Movement of rodents into the area outside should be noted and taken account of.

All rodents can climb. Thus, the survey must take account of the walls and roof spaces of the facility as well as the floors and ground. Subsurface activity, in drains and sewers, should also be identified at this stage.

As well as identifying rodent activity, the trained surveyor will identify faults with the hygiene, as well as faults with the rodent proofing, of the facility. The survey may reveal that control techniques will be more effective if there is a general improvement in the tidiness and hygiene at the site. Removal of spillage and alternative foods as well as the elimination of harbourage may be appropriate. This should not, however, be undertaken if it is likely to make control more difficult by changing the rodents' established behaviour pattern.

The survey stage is also the point at which faults with the rodent proofing of the building can be identified. The types of proofing defect that must be attended to are identified in Fig. 5.2. Some may best be corrected before or during the control operations and others after their completion.

Records should be kept of all findings. Areas of rodent activity should be marked on a map and defects in hygiene and proofing recorded. Managers need access to records to ensure that the survey has been undertaken adequately and also to ensure that the most appropriate control techniques are applied.

APPLICATION OF CONTROL TECHNIQUES. Both non-chemical and chemical control methods are

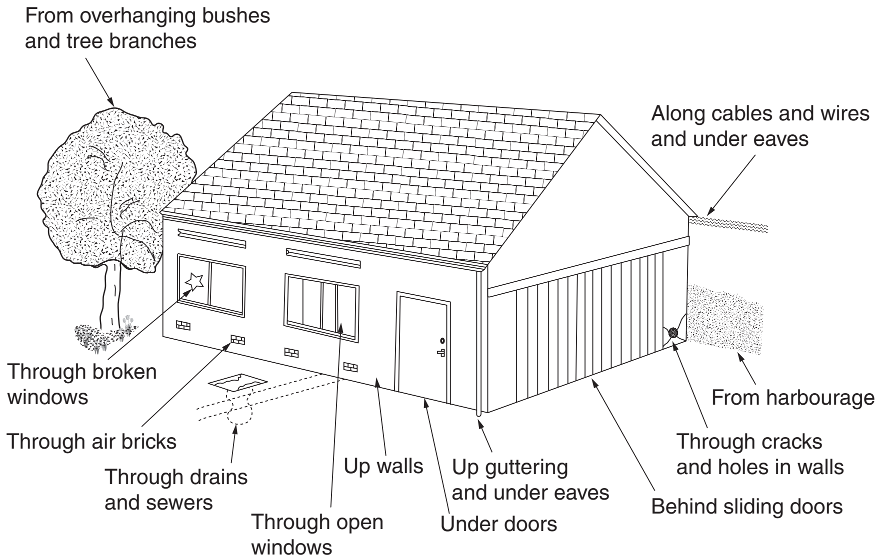

Fig. 5.2. Potential routes and sites of rodent entry into a food-storage facility. A survey will only identify the existing pattern of rodent activity. However, rodent populations are dynamic and, particularly if control measures are applied, activity patterns will change. Continual and regular resurvey of the site will be necessary throughout the control operations and then subsequently.

available for use in the storage environment. The objective should be to achieve 100% elimination of the rodent population from food stores, as otherwise the residual population may rapidly build up to previous levels. The control technique selected should, therefore, be the one that is most likely to achieve 100% control.

Non-chemical techniques (trapping, hunting, predation, etc.), although providing a method of removing some individuals from the population, are rarely likely to achieve 100% elimination of an established infestation. Their use may be required in situations where the use of toxic chemicals is considered hazardous to non-target species, including man, but in these instances their application must be very intensive, leading to high labour costs. Even then, complete removal of sizeable rodent populations is difficult to achieve. Non-chemical techniques, nevertheless, are very important in preventing reinfestation.

In the majority of cases, the main method of control of an established infestation will be the use of chemical rodenticides. Many rodenticides are available (see Chapter 6), and not all will provide the level of control required. A major problem with rodent control in stores is ensuring that the rodenticide bait is sufficiently palatable to attract rodents away from the normally available food source on to the rodenticide in order that they will consume a lethal dose.

It is generally agreed that effective control is best achieved using baits containing delayed-action anticoagulant rodenticides. Rodents can feed on such baits over a number of consecutive days without feeling ill, and it is essential with the less toxic, multiple-feed anticoagulants that the opportunity to feed on baits over a number of days is ensured, thereby increasing the likelihood that a lethal dose is taken. In the case of the more toxic of the second-generation anticoagulants, e.g. flocoumafen, difethialone and brodifacoum, there are increased opportunities to achieve control in the storage environments when alternative feeds to the rodenticide baits are readily available. Anticoagulant rodenticides such as these three are sufficiently toxic to many rodent species to be called 'single-feed' poisons, because lethal doses may be consumed in a day, even if the poisoned bait forms only part of an animal's daily intake. While it is possible for a rodent to ingest a lethal dose in a single day, it should be remembered that not all of the members of a population will do so, and extended treatments will be necessary to ensure complete rodent clearance.

Fast-acting, single-feed rodenticides present a particular problem. To be effective, these so-called 'acute' rodenticides, such as zinc phosphide, strychnine, ANTU (alpha-naphthylthiourea), alphachloralose, red squill, sodium fluoroacetate and fluoroacetamide, all require ingestion of relatively high doses over a short period of time. If a lethal dose is not ingested and the rodent recovers, it may develop both poison and bait shyness, as well as site shyness, which significantly reduce its subsequent susceptibility to any rodenticide treatments. Achieving 100% elimination of a rodent population using fast-acting rodenticides is, therefore, unlikely. Additionally, their high toxicity to man and the associated hazards in the storage environment make acute rodenticides relatively unsuitable for use in food stores.

Some multiple-feed rodenticides that are not anticoagulants also have a delayed effect, e.g. calciferol, reserpine and flupropadine. Here, a lethal dose can be ingested over a longer period of time before feeding ceases, so increasing the opportunity for the ingestion of a lethal dose. Sublethal poisoning may also have a less dramatic effect than the acute (single-dose) rodenticides on subsequent behavioural changes. Such compounds might, then, provide a greater level of success than the fast-acting, single-dose rodenticides. In general, they are found to be less effective than anticoagulants, but they may have a role to play if anticoagulant resistance becomes a significant problem (see Chapter 9).

Although many rodenticides are available in the form of concentrates, and can be mixed with a bait base of the operator's choice, many are now in the form of ready-made formulations presented as either loose cereal or pulse baits, or as pelleted, block or even wax formulations. Selection of the most appropriate bait formulation should ideally be made on the basis of the most palatable formulation available. Even though cost also weighs heavily in these decisions, the primary objective is to eliminate the rodent infestation, and failure is likely to lead to increased long-term costs.

Presentation of rodenticide baits has always been a problem. The need to combine effective with safe presentation of a rodenticide bait in order to avoid poisoning non-target animals means that it may not always be easy to position baits in the ideal place. The use of open bait points without trays is probably best for effective control, but safety constraints may require the use of protected bait points, such as covered trays or boxes, in order to prevent access by non-target species. It is essential, however, that bait points are placed in areas of rodent activity as identified in the survey.

It is desirable to increase the palatability and 'attractiveness' of bait. Attractants have been widely investigated, but with little success, and at present no effective attractant can be recommended. The laboratory palatability of baits may be increased by the addition of sugar and/or edible oils at low concentrations, but these have no significant effect in the field. Flavour enhancers may also be useful in overcoming neophobia (Chapter 1) if the rodents are already used to feeding on these flavours.

Use of an unpoisoned water source adjacent to a bait point may increase bait take from that bait point. Work undertaken against infestations of *R. rattus* in food stores in Sri Lanka (Meyer, 1989) indicated that a significantly higher bait take was obtained from bait points with an adjacent water point than from those without, though similar work undertaken in the UK (A.P. Buckle and A.N. Meyer, unpublished) against *M. domesticus* and *R. norvegicus* failed to confirm these results. Further work on the use of water as a means of enhancing bait take would be desirable.

In addition to the use of edible rodenticide formulations, a number of additional techniques of rodenticide presentation are available, and these are particularly useful in food stores where alternative food sources are available. These alternatives include liquid baits, rodenticide dusts, rodenticide gels and impregnated wicks (Chapter 6).

The use of fumigants such as phosphine can also be an effective method of eliminating rodent infestations, particularly where the infestation is restricted to a relatively small area and can be enclosed or sealed to contain the fumigant. It should be noted that the use of fumigation techniques is very hazardous and should only ever be used by skilled staff fully trained in the appropriate techniques.

MAINTENANCE. A common reason for the ineffective control of rodents in food stores is failure to maintain control operations on a consistent basis. Multiple-feed anticoagulant rodenticides, for instance, require regular visits to the bait points – at least weekly and possibly twice weekly – to record activity, replace bait that has been consumed and reassess the progress of the treatment, making changes in the control treatment as necessary. All too frequently, regular visits are not made, the rodenticide baits are eaten, spilt or become unpalatable, and the rodent population begins to recover from any impact the rodenticide may have had. As a general rule, treatments may be terminated once there have been two visits without a bait take and when no other indications of current activity can be found.

It is essential that, once started, the control treatment is applied appropriately and is taken through to completion. There is little point in commencing control operations unless the resources are available to complete the task. The need for effective management and training is particularly important in this phase of the operation.

HYGIENE. It is far more difficult to control rodents in and around a building that is untidy, dirty and provides the rodents with abundant food and harbourage, than where a building is clean, tidy and provides little opportunity for the rodents to hide and to feed. A major objective of the rodent-control strategy must therefore be to improve hygiene. High standards of hygiene make stores less likely to be infested and make it easier to control rodents if they do arrive.

Inside the store, all equipment and material that is not required for the working of the store should be removed. Materials that have to remain should be stored neatly, preferably in manageable stacks, but never against walls, which would make inspection and survey for rodents difficult. A walkable space of about 1 m should be left around the edge of all stacks.

No material should be stacked directly on the ground; rather, it should be positioned on pallets, shelving or racking off the ground. Ideally, the stacks should be surrounded by a thin strip of chalk dust or fine sand. Any rodents crossing this band leave footprints, showing when rodent activity is present and indicating where control methods or further survey are most appropriate. An essential component of hygiene is to ensure good stock management and stock rotation.

In addition to an effective store-management policy, the store must be kept clean and tidy. At the very simplest level, it will be necessary to ensure that at the end of every working day the store is swept clean, and that all edible and inedible spillage is removed and, if it cannot be reutilized, burned. It is also essential that the hygiene outside the store is given the same degree of attention as that inside. All unnecessary material should be removed, no edible refuse should be allowed to accumulate and vegetation should be kept as short as possible for as large a distance from the store as is practicably possible to discourage rodents. See Lambert *et al*. (2008) for a systematic study of the benefits of hygiene around UK farms.

The maintenance of good hygiene both inside and outside the store must then be part of the rodent-control strategy and is an essential responsibility of the rodent-control team. If the rodent-team members are themselves unable to undertake the necessary work, they should at the very least bring to the attention of the store(s) managers the work that needs to be undertaken. Ideally, of course, the responsibility for both the store management and the rodent control should lie with the same trained manager, thus reducing the opportunity for any conflict of interest.

PROOFING. Although the maintenance of good standards of hygiene will reduce significantly the opportunities for rodent infestation(s) to develop, in isolation they are unlikely to remove the problem altogether. To make them even more effective, they should be combined with an effective proofing strategy designed to make it very difficult for any rodents to enter the store (Jenson, 1979). Rodents are able to gnaw, climb, dig and jump, and because of their inquisitive and exploratory behaviour, are always looking for new, suitable areas in which to live. If we are to protect the store against rodent entry, we must identify not only where they might enter the store (Fig. 5.2), but also how we can prevent entry.

Rodents are good diggers, and as a result, a common point of entry to a store is under the foundations of the building. Sound foundations are likely to be rodent proof. In older or less permanent buildings, however, rodent entry can be prevented by the construction of a concrete curtain wall some 100 mm thick extending not less than 600 mm below ground with the base turned out some 300 mm away from the building in the shape of an L. Openings where pipes, electricity cables, telephone cables, etc., enter the foundations or anywhere else in the building should be sealed with concrete to prevent rodent entry.

Rodents are able to enter buildings through sewers and drains. Sound systems are not usually susceptible to rodent entry and the maintenance of these systems and their inspection for rodent activity should form a part of the survey responsibility for the rodent-control team. If faults are found, they should be corrected, and if a rodent infestation is found in the sewers or drains, then it should be eliminated.

Rodents are also good climbers and are able to climb vertical walls of most brick or concrete buildings; they only need a claw hold. Even smooth surfaces can be climbed if there is a pipe or any construction against which the rodent can brace its back. Rats may reach roofs by using downpipes, which they can climb either inside or outside. Rodents can also enter stores by walking along overhead pipes and cables or by climbing trees that overhang the store.

Proofing against such entry usually involves a variety of techniques. Rodents can be deterred from climbing brickwork or stone by the application of a smooth horizontal band of cement rendering that should then be painted with two coats of a high gloss paint; alternatively, on wooden buildings, a band of smooth metal sheeting can be applied. The bands should be about 20–30 cm wide and should be applied not less than 1 m from the base of the outside wall. External climbing of pipework may be prevented by fixing flat or cone-shaped metal rat guards to pipes high enough above ground level to avoid catching passing vehicles and workers.

Rodents are very good at gnawing and are able to enlarge any small holes or entry points that may be presented to them. Many species can squeeze through extremely small holes; adult mice are able to squeeze through holes of about 12 mm, whereas young mice can only definitely be excluded by holes or gaps of less than 6 mm. All holes in the fabric of the building, the walls, floors, doors or windows should, therefore, be blocked. Holes in floors and walls can usually be effectively proofed by filling with concrete. Essential gaps should be made as small as possible, particularly at the base of doors between the door and threshold. Metal strips and metal kicking plates can be attached to the base of the doors to reduce these gaps.

The exact nature and range of proofing measures that can be applied will depend very much on the design of the store. What is not in doubt is that the identification of proofing needs for a building should lie with the person responsible for rodent control at that site. As the surveys and treatments are undertaken, proofing requirements should be noted. Where proofing measures are relatively straightforward (e.g. filling of holes with concrete), they are probably best undertaken by the rodent-control operator. Where more substantial work is necessary, the details should be passed to the store manager, who must be responsible for their rapid implementation.

MONITORING. It is essential that continual monitoring is undertaken in order that the manager knows the status of the infestation at any point in time. He must ensure that sites that have been satisfactorily treated or, where no current problem is thought to exist, that they are regularly inspected and their status reassessed. To do this, the manager will need a comprehensive survey and recording system so that the degree of rodent infestation in any of the units in his line of responsibility can be identified at any time. A well-designed system will allow him or her to monitor progress and to relate the benefits of the strategy to the costs of the operations.

Cost–benefit analyses of rodent control in stores

Lack of reliable information on losses in stores makes it difficult to justify the costs of control. It is both surprising and disappointing that more emphasis has not been placed on evaluating costs and benefits.

The worldwide survey of rodent damage and control in stores undertaken in the 1970s (Hopf *et al.*, 1976) did identify some estimates of the costs and benefits of rodent-control operations in stores. For example, in Africa, a control programme in stores in Lesotho was reported to have achieved a saving of £1888 at a cost of some £503 (cost:benefit ratio, 1:3), whereas in Swaziland a fumigation undertaken at a cost of £125 was reported to have saved £944 (cost:benefit ratio, 1:6). In Bangladesh, a rodent-control programme undertaken in godowns and houses was reported to have saved £26,740 at a cost of £13,370 (cost: benefit ratio, 1:2). In a larger operation in India undertaken in Gujarat state, a saving of £294,117 was reported with the expenditure of £16,042 on anticoagulant rodenticides, although the additional costs of labour, etc., were not reported. A common characteristic of all these reports is that significant costs and benefits have been obtained in situations of relatively low overall percentage losses due to rodents.

One of the most comprehensive surveys of the costs and benefits of rodent control was undertaken in Cuba (Hernandez and Drummond, 1984). Here, careful monitoring of rodent-control operations in six warehouses identified very high cost–benefit ratios varying between 1:22 and 1:51. These savings were achieved on a relatively low pre-control loss averaging less than 1%, reinforcing the argument that significant cost and benefits can be obtained by effective control even when the original losses are relatively low.

More recently, Lambert *et al.* (2008) described a study on UK farms that showed the effectiveness of various habitat modification measures (e.g. removal of vegetation cover, and other harbourage sites, such as bales, pallets and farm machinery) rather than chemical control. This investigation used radio-tracking data to demonstrate the effects of the measures on the ranging behaviour of Norway rats, and demonstrated that there was potential to reduce the rat population.

The available evidence from cost–benefit analyses suggests that there are significant savings to be made by implementing effective rodent-control strategies in stores. It is important, therefore, that apparently high financial costs are not permitted to restrict the implementation and effectiveness of a control strategy without first assessing the eventual savings that can be made.

Conclusions

The main options available for non-chemical and non-lethal chemical control methods are summarized in Table 5.2; these methods may be cost-effective, but they rarely achieve the rapid knock-down of a pest population that is possible with properly used chemical rodenticides (Chapter 6). Most of the methods can be integrated with chemical control, except perhaps vertebrate predators, which may be vulnerable to secondary poisoning from some persistent chemical rodenticides (Chapter 16). In order to achieve long-term control, the dynamics of the pest population

Table 5.2. Options available for non-chemical and non-lethal chemical control of rodents. The options are grouped according to the population process mainly affected.

Process	Option	Application
Births	Biological sterilization	Field only. Not yet available
	Chemosterilization	Field only. Few options available
	Disruption of behaviour	Varied but largely theoretical
	Removal of nest opportunities	Building design
Deaths	Parasites and disease	Potentially any irruptive field pest
	Predators	Field and store where spatial scales match
	Trapping	Small infestations in buildings
Emigration	Clear cultivation	Field crops after harvest
	Flooding	Irrigated cultivation. Doubtful efficacy
	Hygiene/sanitation	Stores and food processing
	Ultrasound	Limited, and doubtful efficacy
Immigration	Barriers	Small units of high value
	Chemical repellents	Theoretical only at present
	Diversion feeding	Specialized, e.g. wood mouse/sugarbeet
	Electric fences	Small plots at high-value stage
	Rodent proofing	Buildings and stores in good condition
	Ultrasound	Limited, and doubtful efficacy

must be taken into account. In particular, a predator must be able to consume not just the standing crop of pests, but also the turnover (new recruits), in order to prevent natural population increase overcoming the effects of predation.

Exclusion is the most effective method of controlling rodent damage, but in practice it may not always be feasible or cost-effective. Other methods that affect the processes of population dynamics (birth, death, emigration, immigration) need to take account of density dependence, which regulates many animal populations (Sinclair, 1989). The spatial dynamics of the species concerned must also be considered (Shorrocks and Swingland, 1990).

Future developments are likely to involve the genetic engineering of pathogens specific to pests, the development of effective chemosterilants and the use of biological control agents that take account of sublethal effects and of spatial processes.

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6 Control Methods: Chemical

A.P. Buckle[1] and C.T. Eason[2]
[1]*School of Biological Sciences, University of Reading, Reading, UK;* [2]*Centre of Wildlife Management and Conservation, Lincoln University, Lincoln, New Zealand*

Introduction

The benefits of non-chemical methods of rodent control are increasingly recognized (Chapter 5). In particular, the role of environmental characteristics, and their possible modification, in the prevention of rodent infestation is well established (Lambert *et al.*, 2008). Nonetheless, lethal chemical agents – rodenticides – are presently the mainstay of all practical rodent-control programmes that involve the removal of extant infestations. This is true in both urban and agricultural environments and in conservation (Chapter 18), and this situation will remain for the foreseeable future. The reasons for this are the great strides towards the increased safety of rodenticides made with the introduction of the anticoagulants in the early 1950s, and the excellent cost-effectiveness of currently available compounds (Hadler and Buckle, 1992).

The majority of rodenticides are administered as poisoned baits, although some compounds are available in forms that can be used as liquids, contact dusts or poisonous gases. No matter how they are applied, the active ingredients of rodenticides are considered to fall into two categories: the acute, or fast-acting compounds, and the chronic rodenticides, exclusively anticoagulants, with a relatively slow mode of action; reference is also sometimes made to a third group of compounds, the subacute rodenticides (Buckle, 1985), which falls between these two in terms of speed of effect. The calciferols and bromethalin are typical of these substances, but no clear definition of this category exists.

Differences in the characteristics of these groups extend beyond their speed of effect and include contrasts in potency, spectrum, toxicology, hazard, environmental impact, cost, specificity and humaneness. It is useful, therefore, before going on to review the characteristics of these different materials, first to consider generally the desirable properties of a rodenticide.

Optimal Characteristics of a Rodenticide

The requirements of a rodenticide were first comprehensively considered by Gutteridge (1972). His remarkably complete profile, though now over 40 years old, provides a good practical standard by which to judge the potential of a compound to be an effective rodenticide. However, since his list of desirable features was compiled, regulatory requirements have become increasingly stringent.

A number of toxicological, environmental and welfare prerequisites have been added, making it ever more difficult to satisfy the already highly demanding profile. In the first edition of this book, the editors predicted that few, if any, new rodenticides would be introduced in the foreseeable future because of difficulty in satisfying these diverse requirements. This prediction regrettably proved all too accurate. It is even more regrettable that the same prediction still remains true almost 20 years later because the research, development, registration and commercialization challenges facing those who attempt to bring new rodenticides to the market are very great.

Whether the requirements of a successful rodenticide are driven by the intention of regulators to protect human health and the environment, or by industry's need to satisfy these essential considerations as well as to provide efficient and profitable rodenticide products, all relate to two main parameters, efficacy and safety.

Efficacy

Toxicity to target rodents is an obvious prerequisite of a rodenticide. An ongoing trend in rodenticides, though, is towards more complex chemical structures. These bring with them higher costs of manufacture and, as a result, there is a requirement for any new molecules to be increasingly potent so that only small amounts are needed in rodenticide formulations.

Toxicity is closely associated with several other elements of the desired profile that combine to determine efficacy. For example, a compound may be potent but worthless as a rodenticide if it must be used in baits at a strength that is unpalatable to the rodents. The spectrum of activity is also important. Compounds are more useful if they are potent to a wide range of target species rather than specific to a few. Indeed, they may be commercially unviable if their spectrum is restricted. Likewise, within a target species, successful compounds are equally effective against all individuals, independent of sex, age and strain.

A further important influence on efficacy is speed of action. Rodents are unlikely to consume a lethal dose of a poison if the onset of toxicosis is too rapid. Speed of effect, thus, has an impact on the likelihood of a compound eliciting bait shyness (see Chapter 1). Finally, a mode of action that does not induce resistance is a further significant benefit, but it is certainly not one possessed by the anticoagulants (Chapter 9).

Safety

A wide spectrum of activity against different rodent species is an important beneficial feature of a rodenticide, but specificity to rodents is also highly desirable. However, two key target species, the Norway rat, *Rattus norvegicus*, and the domestic mouse, *Mus musculus/domesticus* (Chapter 2), are used as physiological and toxicological models precisely because they exemplify many vertebrate life processes. It has, therefore, proven virtually impossible to develop a rodent-specific poison, although some compounds have useful margins of safety to certain important non-target animals. Rodents form the prey base of predators in many ecosystems and the potential exists for the exposure of predators to rodenticides if they prey upon poisoned rodents or scavenge their dead bodies (Chapter 16). Compounds that are rapidly broken down in the bodies of rodents so that they are not secondarily toxic, are, then, highly desirable.

The need to use rodenticides near man and his domestic animals – because of the commensal nature of these pests – leads to accidental exposure of non-target animals to rodenticides. The availability of a specific antidote is then of great importance. A slow mode of action is also highly beneficial on these occasions so that sufficient time is available to recognize the symptoms of poisoning and administer the antidote. It is the possession of these attributes that made the introduction of the anticoagulant rodenticides such an important step towards increased safety.

Beyond these safety requirements, some of which are easier to attain than others, regulatory agencies also need to be satisfied that the compounds used possess no teratogenic, oncogenic or carcinogenic properties, that they are persistent neither in terrestrial nor aquatic systems and that there is no likelihood of other unacceptable effects on the environment.

A final consideration is that a rodenticide should bring about a humane death. Welfare aspects of rodenticides, and of vertebrate pesticides in general, have become a focus for concern over the last two decades (Chapter 15). The UK, with its Animal (Cruel Poisons) Act 1962, is one of the few countries with legislation imposing this requirement. The European Union's Biocidal Products Regulation (BPR, Regulation (EU) 528/2012) also requires that rodenticides should inflict no 'undesirable effects' on target animals, a clear indication that to gain registration within this regulatory framework a rodenticide must be demonstrably humane.

Acute Rodenticides

Characteristics of acute rodenticides

The origins of some acute rodenticides date back hundreds, if not thousands, of years. The characteristics of the group are extremely diverse but there are common features.

As the name of the group implies, the onset of toxicosis is rapid after an effective dose has been ingested. Generally, symptoms appear in less than 24 h and, with some compounds, in only minutes (Meehan, 1984). Of course, this period is dose related; the effects of poisoning become apparent more quickly when larger amounts of the rodenticide are taken. A definition of an acute compound is one that brings about death, after the administration of a lethal dose, in 24 h or less.

Other common characteristics of these compounds are that they are used at relatively high concentrations in baits, that the molecules are mostly unsophisticated, and therefore cheap to produce, and that they are non-proprietary, and hence unsupported technically by major international companies.

A further important feature of these materials is that few, if any, have a specific antidote. In any case, if antidotes existed, their rapid modes of action would mean that very little time was available for administration. This serious failing, and the high toxicity of some of these compounds to non-target animals, including man, has led to limitations being placed on the availability of the acute rodenticides in many countries. Where acute rodenticides have a place in modern rodent pest management, it may be for use in large-scale control programmes in agriculture (Chapters 12 and 13), and in the removal of invasive species, where repeated use of anticoagulant rodenticides may be less appropriate and the rodenticides are applied by trained professionals. In urban situations, the use of acute compounds is often restricted to premises that can be locked, or to locations, such as warehouses, sewers and ships, that are inaccessible to the public in order further to ensure safety.

The use of acute rodenticides

Many rodent species, particularly rats, are suspicious of new objects (Chapter 1). They are especially reluctant to feed immediately on novel food and may take only very small quantities during initial feeding bouts (Barnett, 1988). This behaviour has a major impact on the use of acute rodenticides. The consumption of a small quantity of bait poisoned with an acute rodenticide is likely to be sufficient to elicit unpleasant symptoms, but not to cause death. The fast onset of toxicosis enables rodents then to associate cause and effect. Affected animals will usually refuse to consume the poisoned food on subsequent occasions and are then said to be poison or bait shy (Prakash, 1988). They may also be reluctant to feed again from bait receptacles, if these were used, and may even be wary of returning to the area in which the poison was taken.

Prebaiting is a method used to increase the likelihood of rodents taking a lethal dose of baits poisoned with acute rodenticides. In this technique, the infested area is first treated with unpoisoned bait of the type to be used in the poisoning programme. The rodents are allowed access to this prebait for several days, until their initial suspicion of the new food has abated and they are feeding freely. The pattern of prebait uptake is usually one of gradual increase until, if the infestation is reasonably circumscribed, a plateau of consumption is reached. This may take several days for mice and up to 2 weeks for rats (see, for example, Quy *et al.*, 1995). The poison is then added to the bait and the poisoned bait laid in the same places, and in the same containers, as the prebait. Usually, the quantity put out needs to be only about half that of prebait consumed during the preceding 24 h because the effect of the poison is quickly to curtail feeding. The majority of poisoned bait consumption will be during the first 24 h of the treatment and, indeed, some authorities recommend that the duration of the poisoning phase should not extend beyond this period. However, experiments with bait markers and Norway rats have shown that some individuals do not feed consistently during baiting programmes (Buckle *et al.*, 1987), and that it may be advantageous to leave baits in position for 2 or 3 days, if it is safe to do so.

Many professional users of acute rodenticides will employ prebaiting strategies, although the concept of prebaiting is a difficult one to get over to those without an understanding of animal behaviour, and is rarely adopted in practice by non-professionals. When acute poison treatments are undertaken by smallholders in tropical agriculture, poisoned bait is laid without prebaiting – a method called direct baiting. There is little reliable information on the efficacy of such treatments, but it is unlikely that they are very effective.

Generally, anticoagulant rodenticides are preferred to acute rodenticides ('acutes') by rodent-control practitioners, for reasons of efficacy and safety. In what situations, then, should acute rodenticides be used?

An advantage of these compounds is their rapid effect. When a valuable crop or stored commodity is heavily infested with rodents, losses can be reduced rapidly, though certainly not entirely, by the use of a fast-acting poison. To gain this benefit, the less effective method of direct baiting must be used because the advantage of speed is lost if effective prebaiting is conducted. A further advantage of acute poisons is that relatively small quantities of bait materials are used during treatments. This can be an asset when rodent infestation is very heavy and the use of an anticoagulant, particularly a warfarin-like compound, would require the application of large amounts of scarce bait materials. Once again, direct baiting must be used to obtain this benefit. In these situations, caution must be exercised in the choice of a bait base during subsequent 'clear-up' treatments with anticoagulants. Survivors of the acute poison baiting may be bait shy and it is important then to use a new bait base to improve the chances of success. Even when this is done, it is unlikely that these combined treatments will be as effective as ones in which anticoagulants are used from the outset.

Acute rodenticides are sometimes recommended for use against infestations resistant to anticoagulants because of their different modes of action. Of course, the use of a different mode of action has the benefit of relieving selection pressure, but it is unnecessary to resort to the use of acutes in many circumstances, because the second-generation anticoagulants (see below) were developed for the purpose of controlling rodents that are resistant to the first-generation anticoagulants, such as warfarin (Chapter 9).

Some commonly used acute compounds

Up to 1950, all rodenticides were non-anticoagulants, most of them acute or fast-acting, but after the introduction of warfarin, and subsequently that of other anticoagulants, the importance of these acute compounds was much reduced. Since the first edition of this book, the need for alternatives to anticoagulants, such as the acutes, has become more pressing as a result of the increased prevalence of anticoagulant resistance, but their use has actually decreased, mainly as a result of regulatory restrictions. The objective of these sections, and of a later one on the subacute rodenticides, is to introduce the important characteristics of these substances, with a focus on those still in use. The principal acute rodenticides used in the USA, Australia and New Zealand are zinc phosphate, sodium fluoroacetate (1080) and cholecalciferol. Bromethalin is also registered in the USA for commensal rodents, and its use may become more prevalent owing to the recent regulatory action of the US Environmental Protection Agency (US EPA). Strychnine is still registered in some countries, for example the USA, for use below ground to control rodents such as pocket gophers and moles. However, in Europe, the use of acute compounds has largely been abandoned, the exception being alphachloralose, which remains authorized for the control of house mice indoors.

A wealth of information exists on many of the acute active ingredients used in rodent control, both in the past and in current use. For more exhaustive reviews of their properties, refer to the works of Hone and Mulligan (1982), Meehan (1984) and Eason *et al.* (2010).

The common chemical names used follow International Union of Pure and Applied Chemistry (IUPAC) nomenclature and the numerals given in (square) brackets following them are CAS (Chemical Abstracts Service) Registry numbers. Table 6.1 provides details of the toxicity of some acute (and subacute) rodenticides to commensal rodents.

Strychnine

Strychnine, strychnidin-10-one, $C_{21}H_{22}N_2O_2$ [57-24-9], is an alkaloid extracted from the seeds of the tree *Strychnos nux-vomica* and has been used worldwide for rodent control since the mid-1800s. It was first recorded in use in Australia in the 1880s and is still used there in the control of mouse plagues (Mutze, 1989). In 1986, the US Environmental Protection Agency (EPA) suspended all above-ground registrations of strychnine, allowing only underground uses (US EPA, 1996). Strychnine products were removed from the market in the European Union because no dossier was submitted for review under the EU's Biocidal Products Directive (EU, 1998). Strychnine is a fast-acting poison but considered inhumane with the typical signs of poisoning being restlessness and muscular twitching, which progress to convulsive seizures and violent muscular spasms before death (Osweiler *et al.*, 1985).

Zinc phosphide

Zinc phosphide (Zn_3P_2), trizinc diphosphide [1314-84-7], is the most commonly used of the acute rodenticides and is the only one widely available for use. It is generally available as a grey or black powder of 80–95% purity, with a strong garlic odour, and is toxic to a wide range of rodent pests (Table 6.1). Zinc phosphide is applied in baits at concentrations ranging from 1 to 5%, although 2% is most widely used. Ready-for-use formulations are available, particularly in the USA.

The mode of action of zinc phosphide is by the evolution of phosphine gas in the acid environment of the stomach; the gas enters the bloodstream and causes heart failure and damage to internal organs. There

Table 6.1. Toxicity (acute oral LD_{50} in mg kg^{-1}) of some acute and subacute rodenticides to three commensal rodents. Where a range is given, the figures represent the smallest and largest values found. (From: Hone and Mulligan, 1982; Meehan, 1984; Brown and Marshall, 1988; and Kaur *et al.*, 2008.)

Compound	*Mus musculus*	*Rattus norvegicus*	*Rattus rattus*
Alphachloralose	190–300	200–400	–
Bromethalin	5.3–8.1	2.0–2.5	6.6
Cholecalciferol	43.6	42.5	30.0–50.0
Ergocalciferol	23.7–42.5	43.6–56.0	–
Sodium fluoroacetate	6.3–16.5	0.2–5.0	0.1–1.0
Strychnine	0.41–0.98	6.0–8.0	–
Zinc phosphide	32.3–53.3	27.0–40.5	21.0

is no specific antidote and the compound is toxic to other vertebrates; LD_{50} values for the pig, dog, cat, chicken and duck are in the range 20–40 mg kg^{-1}.

In spite of its widespread use, surprisingly little information is available on zinc phosphide from well-conducted trials in either the laboratory or the field. Hood (1972) reviewed the effectiveness of the compound for field use in the USA. Rennison (1976) conducted trials on UK farms, using skilled operators, and achieved 84% control of *R. norvegicus* with 2.5% zinc phosphide and prebaiting. This is probably the best that can be achieved from well-conducted zinc phosphide applications. Lam (1977) found the compound to be effective in a field trial in rice fields in Malaysia, but West *et al.* (1975) were unable to demonstrate any effect of repeated zinc phosphide applications in the Philippines.

Nevertheless, there is little doubt that this compound is one of the most effective acute rodenticides currently available, and was probably the most widely used rodenticide for all purposes, including commensal rodent control, until the introduction of first-generation anticoagulant rodenticides. It still remains the toxin of choice for field use in some situations, for example mouse plagues in Australia (Twigg *et al.*, 2002), and can be rapidly broadcast from ground spreaders and aircraft.

Sodium fluoroacetate

Sodium fluoroacetate, $C_2H_2FNaO_2$ [62-74-8], is commonly known as compound 1080 or just 1080. It is highly toxic to rodents (see Table 6.1), and is also used to control rabbits, possums and wallabies in Australia and New Zealand. It is applied in baits containing between 0.08 and 0.5% of the active ingredient. Compound 1080 acts by blocking the tricarboxylic acid cycle, causing the accumulation of citric acid and leading to convulsions and either respiratory or circulatory failure. As this cycle is fundamental in the physiology of vertebrates, the poison is non-specific. Considerable care must be taken when using 1080 in pest control. Primary poisoning of non-target birds and secondary poisoning of dogs must be minimized to ensure that benefits in terms of conservation outcomes and pest and disease control significantly outweigh the risks associated with its use (Eason *et al.*, 2011). Because of the high toxicity of the material, the lack of antidote and its secondary hazard, the use of compound 1080 is carefully regulated in the few countries, like Australia and New Zealand, where it continues to be used.

Alphachloralose

Alphachloralose, (*R*)-1,2-0-(2,2,2-trichloroethylidene)-a-d-glucofuranose, $C_8H_{11}C1_3O_6$ [15879-93-3], is a narcotic with a rapid effect. It slows down a number of essential metabolic processes, including brain activity, heart rate and respiration, inducing hypothermia and eventual death. It is most effective, therefore, against small rodents such as mice, which have a high surface area to volume ratio, and in cool conditions. In the UK, alphachloralose is most often used in baits containing 2–4% of the active material for mouse control. In a number of countries, there is some use of this compound for controlling bird pests and, clearly, because of its toxicity to birds, it must be used with care when applied in baits for control of mice. Recent developments in the European Union (EU) have seen the introduction of several ready-for-use formulations containing 4% alphachloralose (e.g. 'Alphakil'), including a bait containing an encapsulated form of the active substance ('Black Pearl').

Thallium sulfate

Thallium sulfate (also thallium sulphate), Tl_2SO_4 [7446-18-6], is another colourless and odourless crystalline solid. Some authorities also consider it tasteless, but Norway rats are able to detect it in aqueous solution at 0.25%. It was recommended for use in bait at concentrations in the range 0.5–1.5% and, unlike other acute compounds, it seems not to induce bait shyness. In laboratory tests in Denmark, it was most successful against *R. norvegicus* at 0.8%, whereas field trials in the UK showed it to be as effective at 0.3% as 2.5% zinc phosphide (Rennison, 1976). Like other acutes, it suffers from the disadvantages of high toxicity to non-target animals and lack of antidote. It is no longer widely used and is banned in several countries, including Australia, where it was used for rat control in sugarcane fields.

Other acute rodenticides that are no longer widely used

Like thallium sulfate, several other acute rodenticides have been available in the past, but their use in practical rodent control has virtually ceased. These include pyriminyl ('Vacor'), red squill ('Silmurin'), silatrane, gophacide, norbormide, crimidine and ANTU (alpha-naphthylthiourea). Please refer for more information to the works of Gratz (1973), Hone and Mulligan (1982), Meehan (1984), Prakash (1988), Pelfrene (1991), Ray (1991) and Eason *et al.* (2010).

Subacute rodenticides

Bromethalin and the calciferols (ergocalciferol and cholecalciferol) are sometimes termed subacute rodenticides. They have many of the characteristics of the acutes, but differ from them in certain respects. Although rodents may take a lethal dose of these materials during the first 24 h, repeated feeding may occur and death is normally delayed for several days. A further common characteristic of the subacutes is that a period of anorexia may be apparent in animals that have taken both lethal and sublethal doses (Prescott *et al.*, 1992). This is the 'stop feed' action that is commonly claimed as a benefit for these compounds. It is a benefit if a lethal dose has been ingested by the target rodents before the onset of anorexia, but it is a disadvantage if only a sublethal dose is taken and may account for the occasional practical failure of these compounds (e.g. Buckle, 1985). Powdered corn (maize) cob is also reviewed in this section because its speed of action is similar to the above-mentioned compounds, and it does not fit conveniently into any other conventional rodenticide category.

The distinction between acute and subacute compounds is not clear cut, because death may be occasionally delayed beyond 24 h with some acute rodenticides, particularly strychnine and thallium sulfate.

Calciferols

There is some confusion about the compounds known as the calciferols. Ergocalciferol, or vitamin D_2, $C_{28}H_{44}O$, 3β,5*Z*,7*E*,22*E*)-9,10-secoergosta-5,7,10(19),22-tetraen-3-ol [50-14-6], is a naturally occurring compound formerly available as a rodenticide both on its own and in combination with 0.025% warfarin and 0.005% difenacoum, although there is no clear evidence of synergism between the vitamin and these anticoagulants (Greaves *et al.*, 1974). This form of calciferol was tested extensively in the UK both for rat control (Rennison, 1974) and, with warfarin, for mouse control (Rowe *et al.*, 1974), and was particularly effective for the latter. Small doses were thought to be additive over a period of several days, but there is some evidence that sublethal doses cause anorexia and bait shyness (Prescott *et al.*, 1992).

Another form of calciferol, cholecalciferol, vitamin D_3, $C_{27}H_{44}O$, (3β,5*Z*,7*E*)-9,10-secocholesta-5,7,10(19)-trien-3-ol) [67-97-0], was evaluated in the USA, and products under the trade name of 'Quintox' were introduced in the 1980s and remain on the market (Brown and Marshall, 1988).

Products based on the calciferols were removed from the EU market in 2006 when the manufacturers declined to submit regulatory dossiers for review under the European Union's Biocidal Products Directive (EU, 1998). In a recent development, however, a submission has been made to the European Commission (EC) for the registration of cholecalciferol, and products based on this active substance may come back on to the market in Europe in the next few years.

The mode of action of the calciferols in mammals is to stimulate the absorption of calcium in the intestines and the mobilization of skeletal calcium, resulting in hypercalcaemia, osteomalacia and the calcification of soft tissues, particularly the major arteries and kidneys. Treatment of accidental poisoning is symptomatic with cortisone and sodium sulfate.

Bromethalin

Bromethalin, α,α,α-trifluoro-*N*-methyl-4,6-dinitro-*N*-(2,4,6-tribromo-phenyl)-*o*-toluidine, $C_{14}H_7Br_3F_3N_3O_4$ [63333-35-7], is a pale-yellow crystalline solid. Bromethalin is used in baits at either 0.005 or 0.01% and is effective against many rodent species, including those strains resistant to anticoagulants (Jackson *et al.*, 1982). Anorexia occurs after an effective dose has been consumed (Spaulding *et al.*, 1985). The mode of action is by uncoupling oxidative phosphorylation in cells of the central nervous system (CNS). Symptoms of poisoning include tremors, convulsions, prostration and hind-limb paralysis. No specific antidote is available but a symptomatic treatment has been described (Spaulding, 1987). Bromethalin remains in use in the USA (trade names 'Vengeance', 'Fastrac' and 'Tomcat') and elsewhere, but is no longer authorized for use in any of the countries of the EU.

Para-aminopropiophenone

A new acute toxin has come on to the market recently as a result of research conducted primarily in New Zealand. Para-aminopropiophenone (PAPP), $C_9H_{11}NO$ [70-69-0], was registered in New Zealand in 2011 for stoat and feral cat control following the completion of field trials (Shapiro *et al.*, 2010; Dilks *et al.*, 2011). The toxic effects of PAPP are based on its ability to reduce the oxygen-carrying capacity of red blood cells through the formation of methaemoglobin. The onset of symptoms is clearly identifiable and animals receiving lethal doses are usually unconscious within 30–45 min, prior to death within 2 h. Methylene blue will reverse the methaemoglobinaemia induced by PAPP and is considered an antidote; presently, though, PAPP is considered not to be sufficiently potent against rodents to be used as a rodenticide.

Research is under way to improve the performance of the older acute and subacute rodenticides and to seek new compounds, including compounds that are more potent than PAPP, as candidate rodenticides (Rennison *et al.*, 2007; Eason *et al.*, 2011). As indicated above, the research, development and registration challenges to this are very large indeed, and hence the continued importance of the anticoagulants.

Powdered corn cob

Powdered corn (maize) cob [999999-99-4] is composed of selected ground fragments of the woody ring tissue of deseeded corn cobs. The chemical components of this active substance are complex because they are natural products. However, the principle component of powdered corn cob is cellulose (40–45%). Other major constituents include xylan, lignin, pectin and other structural polysaccharides. Powdered corn cob is formulated into bait pellets containing about 90% powdered corn cob for use as a rodenticide. Baits containing powdered corn cob are sold under trade names that include 'Eradibait' and 'Rodetrol'. The labels of these products accentuate the need to remove as far as possible all alternative foodstuffs for rodents when they are applied.

The mode of action of powdered corn cob remains to be fully elucidated, but appears to involve severe perturbation of normal homeostasis because, in laboratory tests, severe weight loss due primarily to dehydration is linked to a reduction of drinking. The humaneness of the mode of action is uncertain (Mason and Littin, 2003). An advantage of the active substance is that, according to the EC Inclusion Directive(s) (see UK HSE, 2013), powdered corn cob presents low risk to humans, non-target animals and the environment.

The properties of rodenticide baits based on powdered corn cob were reviewed by Grech *et al.* (2004). They reported a range of laboratory tests and field efficacy experiments that showed high levels of mortality when powdered corn cob baits were presented to Norway rats and house mice. Schmolz (2010) conducted pen tests against Norway rats and house mice (*M. musculus*) that demonstrated a lack of efficacy and supported the conclusion that cellulose-based rodenticides are unsuitable for the control of these species. Two field trials were conducted against warfarin-resistant Norway rats in Wales, UK, using an approved field trial protocol involving efficacy assessment based on census bait and tracking activity (A.P. Buckle and C. Prescott, personal communication). In the first trial, unsatisfactory control was achieved against a massive infestation (estimated >1400 individuals) inhabiting a farmstead. The second trial involved application against a moderate rat infestation and resulted in estimates of mortality of 81.2% (census bait) and 88.1% (tracking activity). Remnant elements of the infestation were found after baiting in areas where alternative food could not be removed.

The EC has approved powdered corn cob for inclusion in Annex I of the Biocidal Products Directive (UK HSE, 2013). The Rapporteur Member State for the Commission (Greece) has concluded that, as an active substance, the material shows a sufficient degree of efficacy to warrant the evaluation of biocidal products that contain it for authorization. Powdered corn cob is also available in other countries, including Canada and the USA.

The Anticoagulants

Discovery

The discovery of the anticoagulant rodenticides was, without doubt, the most important step ever made towards safer and more effective rodent control. The origins of these compounds are to be found in research conducted in the 1930s in the USA aimed at determining the causative agent of a haemorrhagic disease of cattle. This was found to be a chemical contaminant of spoiled sweet clover hay, dicoumarol (Link, 1944). Further research was aimed at determining the potential of this compound, and a series of synthetic derivatives, for the treatment of human thrombosis. Warfarin, the most active of the synthetic series, was found to have promise as a therapeutic agent and, later, its properties as a rodenticide were recognized (O'Connor, 1948). In the UK, meanwhile, dicoumarol itself was used for rodent control (Hadler and Buckle, 1992), until the superiority of warfarin was demonstrated. The benefits of warfarin over the acute rodenticides were soon identified and, within a few years, this compound, and others like it, came into widespread use, particularly in the developed countries.

Mode of action

The chronic mode of action of the anticoagulants is the key to their success. They act by interrupting the vitamin K cycle in liver microsomes (MacNicoll, 1986). In the functioning cycle (Fig. 6.1), the blood clotting factors II, VII, IX and X are produced as a result of post-translational γ-carboxylation of glutamyl residues to γ-carboxyglutamyl residues. The active form of the vitamin, vitamin K hydroquinone, is required as a cofactor in this process, during which it is converted into the inactive vitamin K 2,3-epoxide. The epoxide is converted into vitamin K quinone by the enzyme vitamin K epoxide reductase (VKORC) and then back to the hydroquinone by the activity of a third enzyme, vitamin K reductase (Cranenburg *et al.*, 2007). Anticoagulants inhibit the epoxide reductase enzymes and block the recycling of the active hydroquinone form of the vitamin (Rost *et al.*, 2009). With this process of recycling blocked, only dietary vitamin K is available and this is insufficient to maintain clotting factor synthesis. For some time after the ingestion of an effective dose of an anticoagulant, sufficient factors are circulating in the blood to maintain clotting, but these are eventually depleted, the mechanism fails and a fatal haemorrhage results (Kerins, 1999). This generally takes 4–10 days. The delay prevents rodents from associating the symptoms of toxicosis with

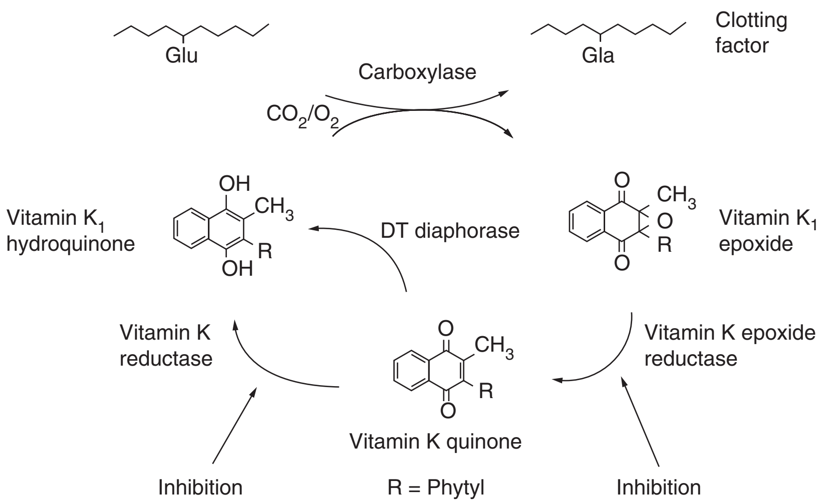


Fig. 6.1. The mechanism of inhibition of clotting caused by hydroxycoumarin-related anticoagulation. The formation of clotting factors is dependent of the conversion of vitamin K_1 hydroquinone into vitamin K_1 epoxide. The K_1 epoxide is then converted first to vitamin K_1 quinone by the enzyme vitamin K epoxide reductase and then back to vitamin K_1 hydroquinone by the enzyme vitamin K reductase. The hydroxycoumarin-related compounds inhibit these reductases and thereby disrupt the recycling of vitamin K_1. DT diaphorase, NAD(P)H:quinone oxidoreductase; Glu, glutamyl residues; Gla, γ-carboxyglutamyl residues.

the anticoagulant that has caused it, so bait shyness is virtually unknown.

This mode of action brings with it a further important benefit. The supply of the active form of the vitamin can be preserved, and the ability of the blood to clot maintained, by the administration of excess amounts of vitamin K_2. Hence, this provides a specific antidote for use in cases of accidental poisoning. Equally important, the chronic mode of action also allows enough time for the antidote to be administered.

The use of the first-generation anticoagulants

During the period 1950–1970, many anticoagulants were commercialized. Collectively, these became known as the first-generation compounds. An important property that governs how they are used is that they are not sufficiently toxic to rodents to cause death after a single exposure. Their action is said to be cumulative but, more accurately, they are effective in blocking the vitamin K cycle for only relatively short periods and must be taken repeatedly, over several days, to have a sufficiently prolonged effect to cause death. Therefore, their successful use in rodent control depends on the target infestation having continuous access to baits over a period ranging from several days to several weeks and, to achieve this, the technique of surplus baiting was developed (O'Connor, 1948). In this, relatively large quantities of bait are put out at bait points, which are frequently replenished to ensure the continuous availability of poison. Baiting continues until the cessation of feeding, which generally indicates that the infestation has been extinguished. Several authors have described this process, which is also termed saturation and sustained baiting (Greaves, 1982; Dubock, 1984).

This technique was widely adopted for the control of commensal rodents throughout the developed world and, with its use, the first-generation anticoagulants came to dominate the practice of rodent control (see Chapters 11–13). Nevertheless, the effective application of anticoagulants with surplus baiting requires a good understanding of their properties, large quantities of materials and the expenditure of considerable effort on the part of the user; these requirements make them largely impractical in the tropics, particularly in smallholder agriculture.

The first-generation anticoagulants are generally effective against most rodent species, when used with surplus baiting, although long periods of feeding may be required in some cases (Table 6.2). However, certain species (e.g. *Meriones shawi* and *Acomys cahirinus*) are so refractory to these compounds, and also to the less potent second-generation anticoagulants, that their use would almost certainly lead to control failure (e.g. Gill and Redfern, 1983). All of the species with natural tolerance to warfarin are xerophilous rodents, living in the arid areas of North Africa and the Middle East. The blood biochemistry of these rodents is worthy of detailed investigation.

Some first-generation anticoagulants

All anticoagulant rodenticides are either hydroxycoumarins or members of a related group, the indane-diones. As the similarity of their structures suggests (Fig. 6.2), they do not differ much in their chemical properties (Buckle, 1993), but variations exist in their toxicity to target rodents. The acute oral LD_{50} is the parameter most widely used to indicate the toxicity of rodenticides, but it is not particularly appropriate with the early anticoagulants. This is because while they are toxic when administered in single, large doses, they are relatively more potent in small doses administered over several, consecutive days. To reflect this, some researchers describe the toxicity of these compounds as a number of repeated daily doses, whereas others have developed the concept of the lethal feeding period (LFP). LFP percentiles are calculated in the same way as lethal dose (LD) and effective dose (ED) percentiles, but periods, normally days of feeding on a bait of standard strength, replace the concentration of active ingredient used as the 'dose' variable (see, for example Buckle *et al.*, 1980). Often, however, LFP data are unavailable and it has frequently been necessary to use LD_{50} values in the following description of the first-generation compounds.

Table 6.2. Natural 'resistance' to warfarin of 11 species of rodents, in order of decreasing resistance. The figures indicate the average number of days required to achieve the lethal feeding period, LFP_{50} or LFP_{99}, respectively, by feeding bait containing 250 ppm warfarin. (From Greaves, 1985.)

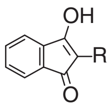
Species	Feeding period (days) LFP_{50}	LFP_{99}
Nesokia indica	1.9	3797.0
Acomys cahirinus	5.4	239.3
Mus musculus	4.8	29.5
Mastomys natalensis	4.8	26.0
Bandicota bengalensis	1.4	25.0
Rattus rattus	3.6	21.0
Tatera indica	5.8	19.2
Rattus argentiventer	3.2	15.5
Sigmodon hispidus	3.7	8.1
Arvicanthis niloticus	3.8	6.0
Rattus norvegicus[a]	1.7	5.8

[a]50 ppm warfarin.

Hydroxycoumarins

WARFARIN. Warfarin, 4-hydroxy-3-(3-oxo-1-phenylbutyl) coumarin, $C_{19}H_{16}0_4$ [81-81-2], was the first anticoagulant widely used as a rodenticide. The compound was introduced in 1950 and, although its popularity has been affected by the widespread development of resistance (Chapter 9), it remains in use the world over.

Values given for the acute oral LD_{50} of warfarin against Norway rats vary between 1.5 and 323 mg kg^{-1} (Hone and Mulligan, 1982), the strain and sex of the test animals and the carrier used in the administration probably affecting the results obtained. The most reliable estimates now place the LD_{50} for warfarin against *R. norvegicus* between 10 and 20 mg kg^{-1} (Meehan, 1984). Warfarin has been widely and successfully used for the control of Norway rats, as this species is the most susceptible of those against which it has been properly tested (Table 6.2). Other species are much less susceptible, and



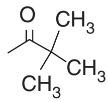
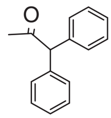
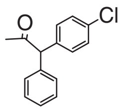
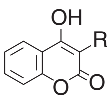
COMPOUND	R
PINDONE	
DIPHACINONE	
CHLOROPHACINONE	

Fig. 6.2(a). Chemical structures of some anticoagulants. First-generation rodenticides: indane-diones. The structure shown at the top of the figure is the base structure, and the substituent R groups are shown below.



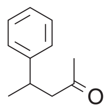
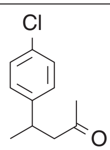
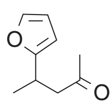
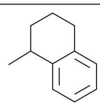
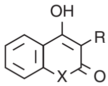
COMPOUND	R
WARFARIN	
COUMACHLOR	
COUMAFURYL	
COUMATETRALYL	

Fig. 6.2(b). Chemical structures of some anticoagulants. First-generation rodenticides: hydroxycoumarins. The structure shown at the top of the figure is the base structure, and the substituent R groups are shown below.



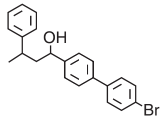
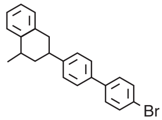
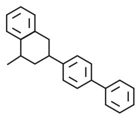
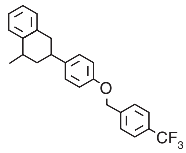
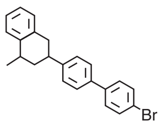
COMPOUND	X	R
BROMADIOLONE	O	
BRODIFACOUM	O	
DIFENACOUM	O	
FLOCOUMAFEN	O	
DIFETHIALONE	S	

Fig. 6.2(c). Chemical structures of some anticoagulants. Second-generation rodenticides. The structure shown at the top of the figure is the base structure, and the substituent R groups are shown below.

Greaves (1985), in presenting the information given in Table 6.2, suggested that warfarin is appropriate only for use against *Sigmodon hispidus*, *Arvicanthis niloticus* and *R. norvegicus*. Rowe and Redfern (1964, 1966) demonstrated a high degree of tolerance to warfarin in 'susceptible' house mouse populations, and the same is probably true for the other important commensal, *R. rattus*.

A wide variety of warfarin formulations is available, under many trade names, including concentrates containing 0.5–1.0% for bait preparation and used as contact dusts (see below), and baits containing 0.025–0.05% of the active ingredient, although liquid concentrates and contact dusts have been largely removed from the market in Europe owing to safety concerns. Mixtures of warfarin with both sulfaquinoxaline and calciferol were used in the past in the proprietary products 'Proline' and 'Sorexa CR', respectively, but the effectiveness of these additives has not been fully demonstrated.

Resistance to warfarin was first discovered in the UK in 1958. It is now established in Norway rat and house mouse populations throughout Europe and North America, in *R. rattus* in several countries and in field rodent populations in South-east Asia (Chapter 9).

Anticoagulants generally produce no carcinogenic, teratogenic and mutagenic effects, but there is evidence that warfarin may adversely affect human fetal development; suggestions that it is also carcinogenic have been dismissed (Pelfrene, 1991). There have been moves by some EU Member States to label all anticoagulants toxic to reproduction by analogy to warfarin because of similarities in their chemical structures and mode of action. However, no such effects have been observed in classical teratology studies for any compound other than warfarin, and manufacturers strongly rebut this assertion.

COUMACHLOR. Coumachlor, 3-[1-(4-chlorophenyl)-3-oxobutyl]-4-hydroxycoumarin, $C_{19}H_{1S}C1O_4$ [81-82-3], was one of several anticoagulants developed in the early 1950s in response to the success of warfarin. Few reliable data are available on its toxicity to rodents. The acute oral LD_{50} is estimated to be between 900 and 1200 mg kg^{-1} for rats and mice (Meehan, 1984), but the compound is more potent in small daily doses, with a chronic LD_{50} of 0.1–1.0 mg kg^{-1} daily for 14–21 days. The active ingredient is recommended in prepared baits at the rate of 0.025–0.05%, and is available as concentrates and contact dusts at both 0.5 and 1.0%. Rats and mice resistant to warfarin are generally cross-resistant to coumachlor. The compound is sold under the trade names 'Tomorin' and 'Ratilan', but is no longer permitted for use in the EU.

COUMATETRALYL. Coumatetralyl, 4-hydroxy-3-(1,2,3,4-tetrahydro-1-naphthyl) coumarin, C19H16O3 [5836-29-3], was first introduced in 1956 and is now one of the most widely used of the first-generation anticoagulants, although it is not available in the USA. The acute oral LD_{50} for Norway rats is given as 16.5–30.0 mg kg^{-1} (Pospischil and Schnorbach, 1994), and the same authors gave a value of 2000–4000 mg kg^{-1} for the acute oral LD_{50} of the compound in mice; as with many of these compounds, coumatetralyl is more potent when administered in consecutive daily doses. The chronic LD_{50} is 0.3 mg kg^{-1} given daily for 5 days for Norway rats and 3.5 mg kg^{-1} for 18 days for house mice (Pospischil and Schnorbach, 1994). A complete kill of mice was obtained in the laboratory only after 21 days of continuous feeding on coumatetralyl bait (Rowe and Redfern, 1968). Laboratory tests indicate that coumatetralyl is likely to be an effective multiple-dose poison for the control of *S. hispidus* and *Mastomys* (*Praomys*) *natalensis* (Table 6.3).

Proprietary baits generally carry 0.0375% coumatetralyl and are sold under the trade name 'Racumin'. Powder concentrates are available in some territories, at 0.75% strength, and used for the preparation of baits and as contact dusts. Baits made from such a concentrate were highly unpalatable to *Rattus argentiventer* (Buckle *et al.*, 1982) but this may have been more due to the inert bait ingredients than to the intrinsic

Table 6.3. Susceptibility of *Sigmodon hispidus* and *Mastomys* (= *Praomys*) *natalensis* to coumatetralyl, difenacoum and bromadiolone. (From Gill and Redfern, 1979, 1980.)

Species	Feeding period	Coumatetralyl (0.0375%)	Difenacoum (0.005%)	Bromadiolone (0.005%)
M. natalensis	LFP_{50}	4.1 (1.9–5.0)	2.5 (2.1–2.8)	0.5 (0.9–7.2)
	LFP_{98}	8.4 (6.4–50.6)	4.8 (4.0–7.0)	4.3 (2.6–56.3)
S. hispidus	LFP_{50}	2.5 (2.0–2.9)	2.2 (1.7–2.5)	1.5 (1.1–1.8)
	LFP_{98}	4.5 (3.7–7.6)	4.3 (3.6–6.7)	5.5 (4.0–10.0)

properties of the active ingredient because Meehan (1984) reported coumatetralyl to be palatable at a concentration of 0.1%.

Indane-diones

DIPHACINONE. Diphacinone, 2-(diphenylacetyl) indan-1,3-dione, $C_{23}H_{16}O_3$) [82-66-6], was first described as a rodenticide in 1952. Acute oral LD_{50} doses against Norway rats are given in the range 2.3–43 mg kg^{-1} (Meehan, 1984). The compound is considerably less active against house mice, with acute oral LD_{50} values calculated at 141 and 340 mg kg^{-1} (Hone and Mulligan, 1982). Diphacinone is not widely used except in the USA, where it is used for rat control and against voles in orchards, although, in orchards, diphacinone was less effective than several other rodenticides tested by Byers (1978). It is used, as the sodium salt, for rodent control in China.

The compound is available, under a number of trade names, including 'Diphacin', 'Ramik' and 'Promar', in a number of formulations, including 0.1–0.5% powder concentrates, pelleted, meal and wax block ready-to-use baits containing 0.005–0.05% of the active ingredient, a 0.1% water-soluble concentrate based on sugar, and contact dusts of up to 2% strength. Generally, higher concentrations are used for mouse control than for the control of rats.

Recently, research has been carried out on diphacinone for the purpose of using baits based on the compound for the control of rats as alien invasives on islands (Howald *et al.*, 2007). The advantage of diphacinone over the compound more generally used, brodifacoum, is its shorter biological half-life (Fisher *et al.*, 2003), though its efficacy may be in question (Chapter 18).

CHLOROPHACINONE. Chlorophacinone, 2-[2-(4-chlorophenyl)-2-phenylacetyl]indan-1,3-dione, $C_23H_{15}C1O_3$ [3691-35-8], was introduced in 1961 and is now widely used in Europe, the USA and elsewhere. The acute oral LD_{50} to *R. norvegicus* is 20.5 mg kg^{-1} (Lund, 1988a), and the compound is applied in baits at a concentration of 0.005–0.01% against these animals. Pelfrene (1991) reported the LD_{50} of chlorophacinone to mice to be 1.0 mg kg^{-1}, but laboratory feeding tests have shown that some mice are relatively tolerant to the compound. In one test, bait containing 0.025% chlorophacinone gave a complete kill of house mice after a 7-day feeding period but, in others, survivors were recorded following 10 and 21 days of feeding (Meehan, 1984). Overall, Lund (1971) and Meehan (1984) considered the performance of chlorophacinone to be about the same as that of warfarin.

The compound has been sold under the trade names 'Rozol', 'Lepit', 'Caid', 'Liphadione' and 'Drat', and is available in a range of formulations, including baits containing 0.005–0.05% chlorophacinone, an oil-based concentrate of 0.25% and a 0.2% contact dust. However, restrictions have been placed recently on the sale of concentrates and dusts in the EU and the USA.

Chlorophacinone is unusual among anticoagulants in that it is said also to act as an uncoupler of oxidative phosphorylation (Pelfrene, 1991); the dosage at which this effect is observed has not been stated.

PINDONE. Pindone, 2-pivaloylindan-1,3-dione, $C_{14}H_{14}O_3$ [83-26-1], was first introduced as an insecticide and only later recognized to have rodenticidal properties. The acute oral LD_{50} against Norway rats is given variously as 50 and 280 mg kg^{-1} (Hone and Mulligan, 1982). Baits containing 0.005–0.05% pindone, and with the trade names 'Pival' and 'Pivalyn', are used for the control of rats and mice, but this compound differs little from warfarin in its efficacy and is no longer much used. In Australia and New Zealand, it is used for the control of rabbits (*Oryctolagus cuniculus*).

Development of the second-generation anticoagulants

Anticoagulant resistance (Chapter 9) was first discovered in Scotland in 1958, when populations of Norway rats proved impossible to control with warfarin and diphacinone (Boyle, 1960). At first, it was thought that coumatetralyl might be successful against warfarin-resistant rodents (Greaves, 1971), but infestations soon appeared that were resistant to this compound as well. These developments threatened the enormous gains that rodent control had made with the introduction of the anticoagulants.

An obvious avenue for those attempting to find an answer to the problem of resistance was research into alternative modes of action. Some chemists, though, reluctant to relinquish the advantages of the anticoagulants, continued to investigate hydroxycoumarin molecules. They noted that the 2-chloro analogue of vitamin K, a known anticoagulant, was more, rather than less, active in resistant rodents (Suttie, 1973). This observation demonstrated that a resistance-breaking anticoagulant might be feasible and further work led to the discovery of a series of molecules with the desired properties (Hadler and Shadbolt, 1975). The first compound commercialized from this series was difenacoum, and this was quickly followed by brodifacoum. In France, chemists had invented a series of warfarin alcohol analogues and one of these, bromadiolone, was introduced as a rodenticide at about the same time and found to be effective against warfarin-resistant rodents. Later, two more molecules, flocoumafen and difethialone, were added to the list of compounds which, collectively, came to be known as the second-generation anticoagulants. These active substances are now, by a considerable margin, the most widely used chemicals for rodent control around the world.

Pulsed baiting

Early development work on brodifacoum, the most potent of the second-generation anticoagulants (Prescott *et al.*, 2007), was focused on its efficiency against warfarin-resistant rats and mice, both in the laboratory (Redfern *et al.*, 1976) and in the field (Rennison and Dubock, 1978). At low concentrations, it was as effective against resistant rodents as warfarin was against fully susceptible animals. However, at higher concentrations, it was so potent that, in the laboratory, complete kills of both susceptible and resistant animals were obtained after only a single day of exposure to poisoned baits. This led to the suggestion that brodifacoum could be used as a 'single-application rodenticide' (Rennison and Dubock, 1978), a sort of 'acute' anticoagulant.

Field trials against warfarin-resistant Norway rats were, therefore, conducted in which brodifacoum bait was applied for limited periods of either 1, 4 or 7 days. The results were disappointing. These regimens produced only 41, 51 and 68% control, respectively. This failure to kill a high proportion of rats after 7 days of exposure to brodifacoum baits in the field was surprising, as only a single day of exposure was almost always fatal in laboratory tests. Rennison and Dubock (1978) suggested that this result may be due to the exclusion of behaviourally subordinate animals from bait points by dominants, although a contributory factor is also likely to be the neophobic responses of some individuals within infestations (Buckle *et al.*, 1987). Whatever the cause, the effect was that baits must be available for longer than 7 days to achieve satisfactory levels of control. It was later postulated (Dubock, 1984) that the rats that took bait during the early stages of these treatments, and succumbed, were likely to have fed repeatedly, thereby consuming more of the brodifacoum bait than was really necessary.

These considerations gave rise to the concept of 'pulsed baiting' (Dubock, 1984) in which small quantities of bait are applied at approximately weekly intervals. Dominant animals, or those that are less neophobic, encounter and consume the baits completely when they are first put out. These die before another application, or 'pulse', of bait is laid for animals that were earlier prevented from taking the bait, either by sympatric dominants or by neophobia. Further pulses are subsequently applied until the population is fully controlled. The value of pulsed baiting for the cost-effective use of brodifacoum was first demonstrated for rice rat control by Buckle *et al.* (1984), and the technique was further developed for use in oil palm plantations

(Khoo, 1984) and on UK farms (Buckle, 1986; Greaves *et al.*, 1988). Critics of the concept suggest that less expert users may run the risk of control failure due to under-baiting. However, experience now shows pulsed baiting to be a robust technique and to have clear advantages, particularly in tropical agriculture, in terms of increased efficacy and reduced bait and labour requirements, over both the use of acute poisons with prebaiting and applications of first-generation anticoagulants using surplus baiting (Kaukeinen and Rampaud, 1986). The system is now integral to the use of the potent second-generation anticoagulants worldwide. A further advantage of pulsed bating is that, having consumed less bait, the dead bodies of rodents present a lower risk of secondary poisoning to non-target animals (Chapter 16).

The second-generation anticoagulants

DIFENACOUM. Difenacoum, 3-(3-biphenyl-4-yl-1,2,3,4-tetrahydro-1-naphthyl)-4-hydroxycoumarin, $C_{31}H_{24}O$ [56073-07-5], was the first compound of the series discovered by Hadler and Shadbolt (1975) to be developed. Early laboratory tests showed difenacoum to be highly active against warfarin-susceptible Norway rats and house mice (Table 6.4) and to be equally effective against rats from the Welsh focus of warfarin resistance, where the resistance mutation Tyr139Ser is present (Hadler *et al.*, 1975); in this, a mutation in the *VKORC1* gene changes a tyrosine to a serine (see Chapter 9). Field trials confirmed the promise of difenacoum, used at 0.005%, for resistance breaking (Rennison and Hadler, 1975). The compound appeared in the market in 1976 and was the first of the new generation of anticoagulants to be commercialized for the control of rodents resistant to warfarin and related compounds. There is also a useful degree of specificity, the compound being generally less toxic to non-target animals than to targets (acute oral LD_{50} in mg kg^{-1}: pig >50; dog 50; cat 100; chicken 50).

Difenacoum is now widely used in rodent control, particularly in Europe and South America, and has recently been introduced to the USA. Many bait types containing 0.005% of the active ingredient are available under trade names such as ‘Ratak’ and ‘Neosorexa’, and they include meals, broken and whole grains, pellets and wax blocks.

Table 6.4. Acute oral LD_{50} (mg kg^{-1}) data for the second-generation anticoagulants against warfarin-susceptible *Rattus norvegicus*, *Mus musculus* and *Rattus rattus*. Where more than one LD_{50} value was found for a species and compound, the lower of the values is given. Where two values are given in the table, they are, respectively, for males and females. (Data from various published sources.)

Compounds	*R. norvegicus*	*M. musculus*	*R. rattus*
Brodifacoum	0.22–0.26	0.40	0.65–0.73
Bromadiolone	0.57–0.75	0.86–1.10	–
Difenacoum	1.80–2.50	0.80	–
Difethialone	0.42–0.56	0.52–0.43	–
Flocoumafen	0.46–0.56	0.79–1.5	1.00–1.80

Resistance to difenacoum was detected in a population of Norway rats in Hampshire, UK, in 1978 (Greaves *et al.*, 1982) and the resistance mutation Leu120Gln has been identified in the *VKORC1* gene. This focus appears to have grown significantly in extent, although the relatively low resistance factors found (Table 6.5) point towards behavioural factors also playing a significant role (Quy *et al.*, 1992). Difenacoum resistance has also been recorded in the UK in mice (Rowe *et al.*, 1981). The resistance mutation Tyr139Cys has been identified in Norway rats in Denmark, France, Belgium, Germany, the UK and Hungary (Chapter 9), and the effectiveness of difenacoum against them is questionable (Lund, 1984; Pelz *et al.*, 1995, 2005). In spite of this, the compound remains widely effective and is one of the most commonly used anticoagulants.

BROMADIOLONE. Bromadiolone, 3-[3-(4’-bromobiphenyl-4-yl)-3-hydroxy-1-phenylpropyl]-4-hydroxycoumarin, $C_{30}H_{23}BrO_4$ [28772-56-7], was patented in 1968 and introduced to the market as a rodenticide in 1976.

In the laboratory, the compound is highly active against warfarin-susceptible rodents (Tables 6.3 and 6.4) and is sufficiently potent to kill susceptible Norway

Table 6.5. Toxicity of anticoagulants to strains of *Rattus norvegicus*, both susceptible and from different foci of resistance. (From Greaves and Cullen-Ayres, 1988.)

	Strain	Sex	LD_{50} (mg kg^{-1}) and 95% fiducial limits
Brodifacoum	Anticoagulant susceptible	M	0.4 (0.35–0.46)
		F	0.49 (0.43–0.56)
	Welsh	M	0.42 (0.37–0.48)
		F	0.56 (0.46–0.73)
	Scottish	M	0.98 (0.78–1.2)
		F	1.3 (1.0–1.6)
	Hampshire	M	0.81 (0.7–0.95)
		F	1.0 (0.4–2.1)
Bromadiolone	Anticoagulant susceptible	M	1.7 (1.3–2.4)
		F	1.5 (1.1–2.2)
	Welsh	M	4.6 (3.5–5.2)
		F	10.4 (8.0–14.0)
	Scottish	M	3.9 (3.3–4.6)
		F	3.8 (2.9–4.9)
	Hampshire	M	2.6 (2.1–3.2)
		F	4.3 (3.5–5.7)
Coumatetralyl	Anticoagulant susceptible	M	0.86 (0.38–1.30)
		F	1.3 (1.1–1.6)
	Welsh	M	29.0 (18.9–103)
		F	219.0 (132–1500)
	Scottish	M	29.2 (23.8–39.7)
		F	73.1 (51.4–330)
Difenacoum	Anticoagulant susceptible	M	1.5 (0.6–2.4)
		F	3.4 (2.3–5.4)
	Welsh	M	1.9 (1.2–2.7)
		F	3.7 (2.4–7.1)
	Scottish	M	5.1 (3.6–6.8)
		F	9.2 (7.2–10.8)
	Hampshire	M	5.8 (2.8–9.2)
		F	14.0 (9.9–24.5)
Warfarin	Anticoagulant susceptible	M	3.4 (2.8–4.6)
		F	2.7 (1.7–4.1)
	Welsh	M	330 (approximation)
		F	6200 (approximation)
	Scottish	M	175 (105–266)
		F	313 (120–5200)

rats after a day of feeding (Redfern and Gill, 1980). Repeated feeding is required to kill resistant rats and house mice (Table 6.6). Bromadiolone is generally used in baits against rats and mice at 0.005% and was effective in the field against Welsh (Tyr139Ser) resistant rats (Richards, 1981). It failed to control house mice in three out of six UK field trials, with one survivor consuming 410 mg kg^{-1} of the active ingredient (Rowe *et al.*, 1981). Similar observations were made in Finland and considered to presage the onset of resistance (Myllymäki, 1986).

Bromadiolone is widely used to control rats and mice in commensal and agricultural situations. The status of the compound in the USA was reviewed by Poché (1986). It is available in a variety of formulations, including cereal-based baits, and oil-based and powder concentrates, containing 0.1–0.5% of the active ingredient, and also as tracking dusts at 0.1–2.0% strength. These are sold under a number of trade names, including ‘Maki’, ‘Contrac’, ‘Super-Caid’ and ‘Bromone’. However, once again, powder concentrates of this active ingredient are no longer permitted for sale in the EU.

Table 6.6. Mortality of susceptible and warfarin-resistant commensal rodents (*Mus* and *Rattus* spp.) after feeding for either 1 or 2 days on baits containing second-generation anticoagulants. Poisons used at 0.005%, excepting difethialone at 0.0025%. (Various sources.[a])

Species (strain)	Anticoagulant	Mortality (%) 1 day's feeding	Mortality (%) 2 days' feeding
M. musculus (warfarin resistant)	Brodifacoum	100	100
	Bromadiolone	5	50
	Difenacoum	0	87
	Difethialone	94	–
	Flocoumafen	75	–
M. musculus (warfarin susceptible)	Brodifacoum	100	100
	Bromadiolone	90	–
	Difenacoum	87	97
	Difethialone	96	–
	Flocoumafen	100	–
R. norvegicus (warfarin resistant)	Brodifacoum	100	100
	Bromadiolone	28	63
	Difenacoum	30	90
	Difethialone	92	–
	Flocoumafen	95	–
R. norvegicus (warfarin susceptible)	Brodifacoum	100	100
	Bromadiolone	100	98
	Difenacoum	90	100
	Difethialone	93	–
	Flocoumafen	100	80
R. rattus	Brodifacoum	100	100
	Bromadiolone	47	90
	Difenacoum	70	100
	Flocoumafen	93	–

[a]Compiled from Hadler *et al.* (1975), Redfern *et al.* (1976), Redfern and Gill (1980), Lund (1981, 1988a,b), Zaghloul and Zakaria (1986), Nahas *et al.* (1989), Gill (1992).

Resistance to bromadiolone has been found in mice in the UK (Rowe *et al.*, 1981), Canada (Siddiqi and Blane, 1982) and (very widely) in Germany (Pelz *et al.*, 2011). At least three different mutations are known to confer resistance to bromadiolone in Norway rats, Tyr139Cys, Tyr139Phe and Leu120Gln (Chapter 9), and these are found widely in European countries including Denmark, France, the UK, Belgium, Germany and Hungary (Lund and Lodal, 1991; Pelz *et al.*, 1995, 2005; Grandemange *et al.*, 2010; Buckle, 2013).

BRODIFACOUM. Brodifacoum, 3-[3-(4'-bromobiphenyl-4-yl)-1, 2, 3, 4-tetrahydro-1-naphthyl]-4-hydroxycoumarin, $C_{32}H_{23}BrO_3$ [56073-10-0], is the most potent of the second-generation anticoagulants (Table 6.4; Prescott *et al.*, 2007). Laboratory and field trials in the UK demonstrated the effectiveness of this compound for the control of resistant rats and mice (Redfern *et al.*, 1976; Rennison and Dubock, 1978; Rowe *et al.*, 1978), and it came on to the market in 1979 (Dubock and Kaukeinen, 1978).

Used in baits at 0.005%, brodifacoum has now been evaluated throughout the world, both in the laboratory and in the field, and shown to be effective against all common commensal and agricultural rodent pests against which it was tested (Kaukeinen and Rampaud, 1986). This work has shown the activity of the compound to be such that rodents usually succumb after consuming bait as part of their food intake on only 1 day. Complete kill of warfarin-susceptible and resistant strains of all three commensal pest species is obtained after 24 h of exposure to brodifacoum baits (Table 6.6). The practical advantages of this high level of activity were demonstrated in trials of pulsed baiting regimes against warfarin-resistant Norway rats (Table 6.7). Commercially available pellet, wax block and cereal baits containing 0.005% brodifacoum are available under the trade names 'Klerat', 'Talon', 'Havoc' and 'Matikus'.

Some populations of *R. norvegicus* have been found in Denmark (Lund and Lodal, 1991) and the UK (Gill and MacNicoll, 1991) that are less susceptible than normal to brodifacoum when tested using baits of, respectively, one half and one tenth of field strength. These rats are now known to carry the Tyr139Cys (Denmark) and Leu120Gln (UK) mutations. This 'low-level' resistance does not pose a practical problem (Lund and Lodal, 1991), as rats are susceptible to full-strength baits.

FLOCOUMAFEN. Flocoumafen, 4-hydroxy-3-[1,2,3,4-tetrahydro-3-[4-(4-trifluoromethylben-zyloxy) phenyl]-1-napthyl]coumarin, $C_{33}H_{25}F_3O_4$ [90035-08-8], was introduced in 1984 (Bowler *et al.*, 1984) and is one of the most potent of the second-generation compounds (Table 6.4). It is less active in non-target bird species than against rodents (acute oral LD_{50} (mg kg^{-1}) values: >100 for chicken; >300 for quail; and about 100 for mallard duck) but apparently toxic to dogs (0.075–0.2 5 mg kg^{-1}).

Flocoumafen is effective against rodent strains resistant to other anticoagulants (Rowe *et al.*, 1985; Buckle, 1986) and is used in a wide range of urban, industrial and agricultural situations (Hoque and Olvida, 1988; Johnson, 1988; Lund, 1988b). Several formulations are available under the trade name 'Storm', including a wax briquette and pellet, both containing 0.005% of the active ingredient.

DIFETHIALONE. Difethialone, 3-[(1RS,3RS;1RS, 3SR)-3-(4′-bromobiphenyl-4-yl)-1,2,3,4-tetrahydro-1-naphthyl]-4-hydroxy-1-benzothiin-2-one, $C_{31}H_{23}BrO_2S$ [104653-34-1], is the most recently introduced second-generation anticoagulant (Lechevin, 1986). Its structure differs from that of brodifacoum in the substitution of sulfur for the oxygen atom in the hydroxycoumarin ring.

As an active ingredient, difethialone is highly potent against warfarin-susceptible and warfarin-resistant commensal rodents (Table 6.4). Laboratory tests have shown 0.0025% difethialone baits to be effective against various strains of rats and mice, both in Denmark and France (Lechevin and Poché, 1988), although a 1 day exposure to the compound at this concentration did not give complete kill (Nahas *et al.*, 1989). Wheat baits containing 0.0025% difethialone gave good control of field voles (Lechevin, 1988), and trials against rats and mice have also been conducted successfully in the USA (Marshall, 1992). Laboratory tests against Tyr139Phe-resistant Norway rats in France (Grandemange *et al.*, 2009) showed that difethialone was likely to be effective against that strain when applied in practice. Difethialone is available in certain European countries under the trade name 'Frap', in the USA under the trade names 'Generation' and 'BlueMax', and more widely around the world as 'Rodilon'.

Regulatory Initiatives

Two major regulatory reviews of the rodenticide active substances have taken place during the last 15 years. In the USA, the

Table 6.7. Efficacy of pulsed baiting applications of 0.005% brodifacoum, bromadiolone and difenacoum (eight replicates of each) against warfarin-resistant Norway rat infestations on Welsh farms. (From Greaves *et al.*, 1988.)

Compound	Average duration of treatments (days)	Average level of control (%)	Number of visits to obtain control	Average weight of bait eaten per bait point (g)
Brodifacoum	22	100	6	82
Bromadiolone	50	90	13	183
Difenacoum	32	96	8	146

Federal Insecticides, Fungicides and Rodenticides Act (FIFRA) has been amended and supplemented since it was introduced in 1972. Under this Act, the implementing agency, the US EPA, required that pesticides registered before November 1984 were to be 'reregistered'; this requirement applied to many rodenticides (see Crescenzi, 2002). Consequently, the US EPA conducted a FIFRA 'data call-in' and a review of rodenticide regulatory dossiers to ensure that they met modern standards. These processes resulted in the publication by the US EPA of a Reregistration Eligibility Document (RED) for the 'rodenticide cluster' that pronounced decisions of the Agency following the review (US EPA, 1998). Two further documents, *Potential Risks of Nine Rodenticides to Birds and Non-target Animals: A Comparative Approach* (Erickson and Urban, 2004), and *Risk Mitigation Decision for Ten Rodenticides* (US EPA, 2008), were subsequently published to impose the required actions on industry in order to mitigate the risks to human health and the environment posed by the use of rodenticides that the US EPA considered to be unacceptable. These documents, and others that support and supplement them, contain a considerable quantity of information that is valuable to those who are interested in rodenticides and their uses, particularly in the USA.

Meanwhile, a similar procedure was initiated in the EU with the enactment of the Biocidal Products Directive (EU, 1998) and the subsequent Biocidal Products Regulation (EU, 2012). All rodenticides, including the acute and subacute rodenticides alphachloralose, zinc phosphide, bromethalin and the calciferols, the first-generation anticoagulants warfarin, sodium warfarin, diphacinone, chlorophacinone and coumatetralyl, and the second-generation substances brodifacoum, bromadiolone, difenacoum, difethialone and flocoumafen, as well as several fumigants, were subject to review. This review, which is ongoing, has been conducted in two phases (Knight and Cooke, 2002; Adams, 2005). In the first phase, data and regulatory studies supporting the registration of the active substances were examined by a Member State regulatory authority nominated by the EC as 'Rapporteur Member State' (RMS). If all studies were found to be compliant with guidelines, and any identified risks to human health and the environment were found to be acceptable, the active substance was listed on Annex I of the Directive (Table 6.8), after a complex process of harmonization between the EC, the RMS and other Member States. When this was achieved, all products placed on the market by industry containing these active substances were themselves reviewed and, where appropriate, authorized for sale. Once again, a considerable amount of information about these chemicals and their uses is now available as a result of this review (see http://echa.europa.eu/regulations/biocidal-products-regulation), and this provides an important resource for those wishing to know more about these compounds. Table 6.8 summarizes the active substances permitted for use in rodenticidal products in the European Union under the provisions of the Biocidal Products Regulation (EU, 2012).

However, the requirement to submit modern, and expensive, regulatory dossiers to the EC for Biocidal Products Directive review in order to remain in the European market has resulted in the loss of several rodenticides because manufacturers have not found it cost-effective to assemble the required dossiers. These include diphacinone, zinc phosphide, bromethalin and the calciferols.

The cost of the modern regulatory dossiers, and the considerable amounts of money and manpower needed to navigate them through the administration of US EPA and EC regulatory processes over the last 15 years, has been a considerable strain on industry resources within a minor sector of the global market for pesticides. There is no doubt that innovation has been substantially curtailed because of the effort involved in defending established active substances and products. We must hope that this considerable expenditure has proved worthwhile in terms of additional protection of human health and the environment (Adams, 2005).

Table 6.8. Active substances (listed by date of Inclusion Directive) permitted for use in rodenticidal products in the European Union under the provisions of the Biocidal Products Regulation (EU, 2012). The renewal of active substance approvals must begin prior to the date of expiry if the active substance is to remain on the market.

Active substance	Date of Inclusion Directive	Date of Annex I inclusion	Date of expiry
Difethialone	29 Nov 2007	1 Nov 2009	31 Oct 2014
Carbon dioxide	24 Jul 2008	1 Nov 2009	31 Oct 2019
Difenacoum	29 Jul 2008	1 Apr 2010	31 Mar 2015
Bromadiolone	31 Jul 2009	1 Jul 2011	30 Jun 2016
Alphachloralose	31 Jul 2009	1 Jul 2011	31 Jun 2021
Aluminium phosphide	31 Jul 2009	1 Sep 2011	31 Aug 2021
Coumatetralyl	29 Jul 2009	1 Jul 2011	30 Jun 2016
Chlorophacinone	4 Aug 2009	1 Jul 2011	30 Jun 2016
Flocoumafen	27 Nov 2009	1 Oct 2011	30 Sep 2016
Warfarin sodium	9 Feb 2010	1 Feb 2012	31 Jan 2017
Warfarin	9 Feb 2010	1 Feb 2012	31 Jan 2017
Brodifacoum	9 Feb 2010	1 Feb 2012	31 Jan 2017
Powdered corn cob	30 July 2013	1 Feb 2015	31 Jan 2025

Rodenticide Formulations

General considerations

Irrespective of their chemical composition, rodenticide compounds are always modified by a formulation process to facilitate their use. They may be sold by manufacturers in the form in which they are to be ultimately applied, so-called ‘ready-for-use’ formulations, or they may require some modification by the practitioner. Most rodenticides are employed in baits, in which the active constituent is mixed with an edible base attractive to rodents. Some products are available in forms that make them suitable for use in liquid bait preparations, as contact poisons and as concentrates for bait preparation by users. These latter formulations are increasingly restricted because of regulatory concern about operator exposure during bait preparation when adequate containment and personal protective clothing is not used.

Most rodent pests are omnivorous, but cereals form an important dietary element for the majority of species. For this reason, and because they are widely available and easy to store in good condition, cereals are commonly used as base materials for rodenticide baits. The cereal selected will depend, among other factors, on cost, local availability and, when baits are prepared by users, on the preference of the operator. All types of cereals have been used successfully, including wheat, rice, maize, oats, barley, millet and sorghum, and none has been found to be universally favoured by rodents. A general rule is that the cereal used should be of the highest grade available; it is a false economy to use a bait base of low quality, both for manufacturers preparing baits for sale and for operators making them for their own use.

A good-quality cereal is normally, on its own, sufficiently attractive to rodents to produce excellent results when used with an effective rodenticide. Various attractants, among them fruit, meat and fish flavourings, molasses, cinnamon and aniseed, are sometimes added to baits as well (Marsh, 1988). Usually, these additives appeal more to human purchasers than to the rodents that are the ultimate ‘consumers’ of bait preparations. Some in the pest control industry claim to possess ‘magic ingredients’ that make their baits ‘irresistible’ to rodents. Scientific tests rarely bear out these claims (Meehan, 1984), but certain edible oils are known to enhance bait uptake by rodents and, for this reason, one of them, corn (maize) oil, is a component in a challenge diet advocated by the US EPA and frequently used in palatability testing (Chapter 7). Sugar is also used in this 'EPA meal', as it too is known to increase the palatability of rodenticide preparations.

It is normal practice when producing bait on a commercial scale to include a dye or pigment. Chosen appropriately, shades of either blue, black or green are frequently used; the colour serves as a warning that the bait is not a human foodstuff. The addition of a warning dye in rodenticide baits is now mandatory in the EU. There is also some evidence that certain colours, particularly blue, are less readily perceived by birds, and this adds another benefit to their inclusion in baits.

Cereal-based baits used in dry environments stay in good condition for long periods but are prone to rapid deterioration where there is warmth and high humidity. Preservatives added to inhibit mould growth in baits, such as para-nitrophenol and dehydroacetic acid, were never entirely satisfactory because they depressed palatability. The development of wax block formulations has rendered them largely redundant.

Concentrates

Some manufacturers market rodenticide concentrates that are used by the pest-control practitioner, in conjunction with selected cereal bases, to produce baits. These are often favoured because the finished baits are cheaply produced and permit the addition of favoured additives. In the past, concentrates were formulated as powders and dusts, but these have been mostly superseded by liquid formulations to eliminate the risk to users of inhaling anticoagulant dust particles during bait mixing.

Notwithstanding this significant improvement, handling rodenticide concentrates is inherently hazardous and requires the strict observance of safety rules. These include, but are not restricted to, the use of appropriate protective clothing by workers, adequate bunding on factory floors to contain any likely spillage of liquid, frequent health checks for workers, proper facilities for cleaning contaminated equipment, means for the safe disposal of liquid effluent, solid wastes and contaminated containers, and air extraction to remove the fine dust particles that are usually produced during bait manufacturing processes.

Increasingly, legislation, such as the UK Control of Substances Hazardous to Health (COSHH) Regulations and equivalent rules in other EU countries, restrict those permitted to manufacture baits to large formulators who are prepared to invest the considerable sums of money now required to build and maintain safe and efficient production facilities. It is a provision of the sale of many of the anticoagulants in the EU under the rules of the Biocidal Products Directive (EU, 1998) that concentrates are no longer available to users but only to industrial manufacturers.

Baits

Cereal grains, either whole, broken, rolled or ground, produce satisfactory rodenticide baits and are widely used both by large manufacturers and small-scale formulators. A 'sticker' may be required if whole grains are used in conjunction with a dust concentrate. The sticker is usually an oil, which serves both to bind the dust to the cereal grains and to reduce the hazard of dust particles being evolved during mixing, and may also act as an attractant. Oils quickly go rancid, however, and are not much used commercially.

No matter what process is used in the production of grain baits, all baits made in this way suffer the disadvantage that the active ingredient is present only on, or near, the surface of the grains. This can lead to problems of palatability, if the active ingredient or concentrate is intrinsically unpalatable (e.g. Buckle *et al.*, 1982), and under adverse weather conditions the active ingredient may separate from the bait matrix.

The production of rodenticide baits using cereal grains that are recognizable as human foods causes justifiable concerns of product stewardship. On rare occasions, people faced with starvation have turned to treated grain, either by accident or purposefully, as a source of sustenance. Fortunately, such episodes are extremely rare, but it is important that those distributing rodenticides in areas where food shortages may occur bear this in mind.

In an attempt to overcome some of the problems associated with grain baits, manufacturers have produced a number of formulations based on different production processes. One of the first of these to be commercialized was rodenticide pellets. These are made using technology similar to that employed in the production of animal feeds. Finely milled cereals are mixed with an active ingredient concentrate and forced under pressure through a die. Heat is employed to alter the biochemical composition of the mixture so that it is firmly held together after extrusion. Some processes rely only on the heat generated by compression, whereas others utilize an external source such as steam. The size of the die determines the size and shape of the finished product.

Pellets are usually very palatable because they contain a high proportion of cereal components and the active ingredient is uniformly dispersed through the grain matrix. Their acceptance by rodents is influenced by their size, shape and hardness. Pellets are preferred for use in all commensal situations, particularly indoors and where the bait is deployed in bait boxes. They tend to disintegrate if exposed to moisture but their weatherability can be improved by the addition of a quantity of wax to the cereal premix during manufacture. Pellets are not well suited to use in agriculture because, like grain baits, they may be taken by granivorous birds.

Problems with pellets of poor weatherability and hazard to birds led to the development of rodenticide wax blocks. These products are also mainly composed of cereals, either whole, broken or milled but, in addition, they contain a substantial proportion, usually 15–40%, of paraffin wax. They are produced by a number of different processes; some are cast after all the ingredients are melted together, others are made by a briquetting process, and a third type is manufactured by extrusion. The process of manufacture influences the properties of the blocks. Those made by the casting of a finely particulate matrix tend to withstand exposure to moisture better than blocks made by compression and those containing relatively large cereal particles.

Wax block formulations are generally accepted to be somewhat less palatable to rodents than those based almost entirely on cereals. Then again, because of their advantages of safety to non-target animals (Johnson, 1988; Chapter 16) and their practical benefits of ease of application and weatherability, wax blocks are particularly appropriate for use in open-field agriculture. Indeed, they were first employed for the control of rats in coconut plantations in the Caribbean (Smith, 1967), and also came into early use for oil palm (Wood, 1969) and rice (Wood, 1971; Buckle *et al.*, 1984) in Malaysia. They are used in commensal control programmes in damp locations, such as sewers, rodent burrows and other outdoor sites; they are also used for permanent or maintenance baiting in bait boxes. In spite of the fact that wax blocks may be less palatable than cereals (see Schmolz, 2011), such blocks are widely used for rodent control, both by pest control professionals and amateurs. However, as a result of behavioural experiments with Norway rats in large enclosures, Quy (2012) concluded that 'little rodent control will be achieved' when wax blocks are anchored in tamper-resistant bait boxes.

A recent development in bait technology has been the introduction of the paste or 'pasta' baits. These are produced using a wide range of materials, but they generally contain finely particulate cereals held together as a soft paste with fats, oils or gelling agents. The paste is either presented as a 'unit dose' in a sachet made from paper or a polymer, or is dispensed using a caulking gun. Pasta baits are often claimed to be particularly attractive to rodents but, in standard laboratory palatability tests, they rarely perform better than high-quality cereal baits.

Other bait formulations are occasionally used in control programmes. Baits formulated as liquids may be effective where water is scarce and the food available to rodents is predominantly dry, such as in grain stores and cereal mills. Soluble forms of anticoagulants are dissolved in water and presented from drinking fonts. Chicken drinkers are often used for this purpose. The evaporation of water from liquid baits causes problems of acceptance, as the active ingredient becomes more concentrated, and it is necessary to site the bait points carefully to avoid disturbance and spillage.

Denatonium benzoate

A useful advance towards the increased safety of rodenticidal preparations was the introduction of the human taste deterrent denatonium benzoate, *N*-[2-[(2,6-dimethylphenyl) amino]-2-oxoethyl]-*N*,*N*-diethylbenzenemethanaminium benzoate, $C_{28}H_{34}N_2O_3$ [3734-33-6], trade name 'Bitrex' (owned by Macfarlan Smith Limited, UK). This compound is highly repellent to humans when included in baits at a strength of 0.001%, but does not deter their consumption by rodents (Kaukeinen and Buckle, 1992). Other concentrations of the compound are also used in some bait formulations. The incorporation of this compound is unlikely to decrease the frequency of accidental exposure of humans to baits, but it helps to reduce the quantity of bait accidentally consumed and, thereby, the clinical severity of these incidents. Claims are occasionally made that denatonium benzoate may prevent accidental consumption of bait by non-target animals, but there is no published evidence that any concentration of the compound that is acceptable to rodents is repellent to other animals.

Contact poisons

Dust and gel formulations are available as 'contact poisons', but these are not contact poisons in the conventional sense, because they do not cause death on skin contact. They are applied to burrows, harbourages and surfaces over which rodents pass. The rodents' feet and fur become contaminated and the poison is ingested during grooming. The advantage of these formulations is that their efficacy is not affected by the presence of attractive alternative sources of food.

Contact dusts, or tracking dusts as they are sometimes called, vary greatly in their composition. Their efficiency is influenced by particle size, and the most effective formulations are those that are attracted by the electrostatic forces generated by the fur of the target animals. Because only a relatively small amount of the poison is picked up and taken in, rodenticide dusts usually carry a concentration of the active ingredient 20 times higher than a bait containing the same compound. For this reason, and because dusts readily become airborne and may be transported to areas where food is prepared and stored, great care is required in their use. The availability of contact dusts is increasingly limited by regulatory concerns because of the relatively high concentrations of active substances that they contain and the mobility of these formulations.

Contact gel formulations do not have the same potential to contaminate the environment as dusts. They are used mainly by pest-control operators (PCOs), and specifically for mouse control in the form of tunnels with toxic wicks impregnated with brodifacoum (Morris and Kaukeinen, 1988), and dispensed on to surfaces from a caulking gun apparatus. However, traces of these gels may be found some distance from their site of application, transferred from bait receptacles on the fur and feet of target rodents.

Fumigants

These materials are used for rodent control in situations where conventional methods, such as baits and contact poisons, are either ineffective or impractical (Meehan, 1984). Usually, sites treated with fumigants are installations that can be sealed effectively or enclosed in a gas-tight membrane, for example ships' holds, aircraft, grain silos and warehouses. Fumigants are available formulated as powders, impregnated cardboard discs, pellets and tablets, and as gases in steel cylinders. Great care is required in the application of all these formulations and, in many countries, only specially trained pest control professionals are permitted to use them.

One of the compounds now most commonly used for fumigation is phosphine (PH_3). This gas, which is evolved when either magnesium phosphide or aluminium phosphide formulations are exposed to atmospheric or soil moisture, is mainly used for the control of infestations of stored product insects, but these applications are also efficient against rodents. Methyl bromide (CH_3Br) is similarly effective but now very little used. Other fumigants used less frequently in a similar fashion are chloropicrin (CCl_3NO_2), carbon dioxide (CO_2) and carbon disulfide (CS_2).

Fumigants are also used for gassing rodent burrows. In these operations, either pellets or tablets containing aluminium or magnesium phosphide are inserted into rodent burrows, which are then sealed with soil. The gases evolved build up to concentrations lethal to the burrow's occupants. Hydrogen cyanide (HCN) gas may by similarly used and is under evaluation in the EU for use as a rodenticide in a formulation in which the gas is absorbed on to a porous material ('Uragan D2').

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7 The Laboratory Evaluation of Rodenticides

C.V. Prescott and R.A. Johnson
School of Biological Sciences, University of Reading, Reading, UK

Introduction

Rodenticides are chemical substances used for killing rodent pests (generally through ingestion). The most important features of a rodenticide that contribute to its performance are its toxicity and palatability, both of which are largely assessed in the laboratory. Much of the considerable effort involving the laboratory evaluation of rodenticides is aimed at meeting the increasing demands of various regulatory bodies. The cornerstone of rodenticide regulation is registration, and the basic data requirements needed to achieve registration (i.e. specifications, efficacy and toxicology) are now largely standardized. Rodenticide registration in any particular country varies in complexity depending on the facilities and expertise available. In most developed countries, comprehensive registration schemes are enforced and this is reflected in the availability of appropriate documentation. In the USA, for example, rodenticides are evaluated using the Environmental Protection Agency (EPA) Guidelines (US EPA, 1982) and in the European Union (EU), test methods are based on the guidelines linked with Directive 98/8/EC, known as the European Biocidal Products Directive, or BPD (EU, 2009).

In many developing countries, a more pragmatic and simplified approach to rodenticide evaluation and subsequent registration has been adopted. Where biological efficacy data requirements against local pest species have been introduced, test methods have tended to be based on guidelines of either the EPA (US EPA, 1982), the European and Mediterranean Plant Protection Organization (EPPO, 1999) or the BPD (EU, 2009; recently superseded by Regulation (EU) No 528/2012). A truly harmonized approach promoting the scientific aspects of testing to avoid wasteful duplication or repetition is, therefore, lacking.

More recently, a general concern for animal welfare has led to the search for alternative methods of toxicity testing that do not require the use of large numbers of animals. For the laboratory evaluation of rodenticides, there are no practicable alternative methods to tests involving the use of significant numbers of the target species. However, in some countries, legislation has been introduced that is intended to promote a reduction in the number of animals used in testing. Furthermore, in the UK and in recent EU legislation, in addition to toxicity and palatability testing, rodenticide registration now takes into account the humaneness of the active ingredient.

The sets of guidelines referred to above include comprehensive series of test methods to be used in the evaluation of the toxicity and acceptability of a rodenticide, from its preliminary screening as a potentially useful chemical to its final evaluation in the field in some suitable formulation. Reference should be made to the published guidelines for the appropriate details (US EPA, 1982; EPPO, 1999; EU, 2009).

The aim of this chapter is to review the principal elements involved in the laboratory evaluation of rodenticides. Although it is not yet possible to devise 'standard' test methods appropriate for all target species, the chapter highlights, where appropriate, key areas for possible harmonization. In addition, the complex issue of humaneness will be discussed. Evaluation of other important aspects, such as non-target hazard assessment (see Chapter 16) and stability, are not included.

Test Animals and Their Care

The laboratory evaluation of rodenticides can, for convenience, be divided into two parts: tests on caged rodents, singly or in small groups; and tests on groups of rodents in rooms or pens. In all cases, it is important to standardize as much as possible the test animals that are used and their maintenance.

For considerations of a logistic nature such as cost, availability, ease of breeding and handling under experimental conditions, laboratory strains of the cosmopolitan synanthropic species the Norway rat and the house mouse are preferred for tests on caged rodents. Ultimately, it may be necessary to perform tests on wild rodents, and in some countries, this is the only option. Certainly, the use of commonly available laboratory strains promotes some degree of harmonization. Indeed, deviation from normality and increased variance in data sets generated using wild-caught rodents complicates subsequent analysis.

Test rodents should be healthy, active and sexually mature. Animals should fall into a specified weight category before the beginning of the test. Generally, the weight variation in animals used in routine toxicity testing should not exceed ± 20% of the mean weight (OECD, 1987). Table 7.1 gives examples from the EPA, EPPO and BPD guidelines.

Table 7.1. Examples of size variation in test animals allowed by the US Pesticide Assessment Guidelines (US EPA, 1982), European Guidelines for the Efficacy Evaluation of Plant Protection Products (EPPO, 1999) and the European Biocidal Products Directive (BPD) (EU, 2009).

Guidelines	Acceptable weight range (g) Minimum	Maximum	Maximum acceptable differences in average weights between sexes (g)
EPA			
Norway rat			
Albino	150	300	
Wild	150	400	
Roof rat	100	225	40
House mouse			
Albino	15	35	5
Wild	10	25	3
EPPO			
Norway rat			
Albino	100	150	(Not specified)
Wild	Wide weight range		(Not specified)
House mouse	20	25	(Not specified)
BPD			
Norway rat			
Albino	150	(Not specified)	(Not specified)
Wild	150	(Not specified)	(Not specified)
House mouse	15	(Not specified)	(Not specified)

Stringent control of environmental conditions and proper animal care techniques are mandatory for meaningful results. The behaviour of an animal, for example, can be adversely affected by unstable or unfavourable environmental conditions. Examples of the variations in standardization of the important environmental conditions in the UK (Animals (Scientific Procedures) Act, 1986; see UK Home Office, 1995) and the USA (Institute of Laboratory Animal Research, 2011) are summarized in Table 7.2a. The test cages should have wired grid floors suspended above trays to assist in the separation of food spillage and to reduce the contamination of food spillage by urine and faeces. Cages normally have solid sides to reduce interactions between neighbouring animals. In some countries, minimum floor areas and cage heights are specified for certain species (Table 7.2b).

The pretest conditioning of animals is most important. In general, animals received from a commercial supplier should be held in the laboratory, group caged and sexes separate, for a minimum period of 1 week to confirm that they are healthy. After weighing, they are then transferred to the test environment (singly caged) and allowed to acclimatize.

Food consumption is monitored daily and acclimatization is usually considered to be complete when the animals have established a pattern of regular daily consumption. For laboratory-strain animals, acclimatization is usually achieved within 1 week. For wild-captured rodents, acclimatization can take up to 3 weeks. The diet should meet all the nutritional requirements of the species used in the test, and conventional commercial laboratory diets may be used with an unlimited supply of drinking water. For microtine and other field rodents, both wild and laboratory-bred animals may be used in cage tests. Their maintenance diet may be a commercial balanced pelleted diet supplemented with lucerne, clover or dried hay and fodder beets or other root crops.

The number and size of the groups of animals used in the laboratory evaluation of rodenticides is very variable. Taking into account the inherent variability of biological

Table 7.2. Examples of environmental requirements for test animals: (a) test room; (b) minimum cage dimensions. (From the (UK) Home Office, 1995; and the (US) Institute for Laboratory Animal Research, 2011.)

(a) Environmental variables

	UK	USA
Temperature (°C)	19–23	20–26
Relative humidity (%)	40–70	30–70
Light intensity (lx)	350–400	325–400
Light photoperiod	12 h light/12 h dark	‘Regular diurnal cycle’
Ventilation (air changes/h)	8–30	10–15
Noise	<50 dB	Minimum disturbance

(b) Minimum cage dimensions

	Minimum floor area (cm^2 per animal)	Minimum height (cm)
UK Guidelines		
Rats	500–800[a,b]	18–20
Mice	200[a]	12
US Guidelines		
Rats	109.6–800[c,d]	17.8
Mice	38.7–330[c,d]	12.7

[a]Including area taken up by food bowls.
[b]Increases in relation to body weight.
[c]Excluding area taken up by food bowls.
[d]Large animals may require more space to meet performance standards.

systems, there must always be a balance between the number of animals required to give a statistically acceptable response (the degree of accuracy required) and ethical and welfare considerations. EPPO (1999) considered five animals per group to be satisfactory for preliminary tests, but suggested at least 20 animals where the outcome of a test is regarded as crucial. The EPA recommends at least five male and five female animals for each of three dose levels in the assessment of acute oral toxicity (US EPA, 1984) and ten male and ten female animals per test for efficacy assessment (US EPA, 1982). The BPD Guidelines require groups of five male and five female animals per test for efficacy assessment (EU, 2009). In some countries, untreated control animals are also included in toxicity-testing protocols.

In summary, good control of environmental conditions (temperature, humidity, lighting, ventilation and noise), combined with a standardized diet, competent handling and routine cleaning, will undoubtedly improve the quality of the data generated and consequently minimize animal use. Furthermore, the introduction of the principles of good laboratory practice (GLP), which facilitate the proper conduct of studies, promote full and accurate reporting and provide the means whereby the integrity of the studies can be verified, will allow the further refinement and harmonization of test protocols.

Tests on Caged Rodents

The laboratory cage tests considered here are summarized in Table 7.3. The test sequence is designed to evaluate the toxicity and acceptability of rodenticides (the active ingredient) and rodenticide baits, and to determine the time delay for the development of symptoms that cause a reduction in feeding. Evaluation of other minor-use preparations, such as contact formulations, is considered elsewhere (US EPA, 1982; EPPO, 1999).

Rodenticides have traditionally been characterized as belonging to one of two classes (Chapter 6):

- acute poisons (single feed, quick acting, i.e. less than 24 h from lethal dose to death); and
- chronic poisons (multiple feed, slow acting, i.e. several days from lethal dose to death).

This classification has become ambiguous since the introduction of the more potent second-generation anticoagulant rodenticides, which have single-feed potency but are also slow acting. Thus, three classes of rodenticides are now proposed:

1. Single-dose fast-acting rodenticides, e.g. zinc phosphide.
2. Single-dose slow-acting rodenticides, e.g. brodifacoum, flocoumafen.
3. Multiple-dose slow-acting rodenticides, e.g. coumatetralyl, warfarin.

However, there may not always be a clear demarcation between the two classes of slow-acting rodenticides.

Single-dose oral toxicity

Determination of single-dose oral toxicity is usually the initial step in the evaluation of new rodenticides. The main scientific objectives are summarized in Table 7.3. Details of the test method used to determine the median lethal dose (LD_{50}) are described elsewhere (e.g. EPPO, 1999). In outline, the test substance is administered orally by gavage in graduated doses to several groups of experimental animals, one dose being used per group. The LD_{50} may be estimated by analysis of the dose mortality data using any accepted statistical method (e.g. Horn, 1956; Finney, 1971).

LD_{50} estimates for some rodenticides may vary from study to study, and between and within species, because single-dose oral toxicity is influenced both by internal and external factors. In addition to the need for standardized housing and feeding conditions referred to earlier, other variables can include nutritional status of the animals and the carrier vehicle used.

It is the practice in many laboratories for test animals to fast before substance administration, in order to minimize any

Table 7.3. A workflow scheme based on UK guidelines for testing rodenticide efficacy.

Tests on caged rodents	Scientific objectives
Single-dose oral LD_{50}[a] (single- and multiple-feed rodenticides) Other tests	To evaluate basic toxicity to the target species To establish toxicity relative to other rodenticides To provide information on the mode of action To generate regulatory hazard classification data
Multiple-dose oral LD_{50}[a] (multiple-feed rodenticides)	To evaluate basic toxicity To compare with single-dose oral toxicity To select concentrations of the active ingredient in subsequent feeding tests
No-choice feeding[a] (single- and multiple-feed rodenticides)	To evaluate free-feeding toxicity To evaluate bioavailability of the active ingredient in the proposed formulation
Choice feeding[a] (single- and multiple-feed rodenticides)	To evaluate acceptability of active ingredient in a bait formulation (palatability) To determine the time delay for the development of symptoms that cause a reduction in feeding

[a]These tests would also be used to evaluate the humaneness of the rodenticide and of rodenticide preparations.

effect of differences in the amount of food in the gut and subsequent gut absorption and motility (though this information is not always reported). In the USA, for example, the EPA (US EPA, 1984) recommends for rats that food should be withheld overnight, whereas for other rodents with higher metabolic rates a shorter period of fasting may be appropriate. In the UK, fasting for 6–18 h before administration of the test substance is permitted, although the EPPO guidelines do not specify the need for any fasting.

The test substance, if a solid, should be finely ground, and dissolved or suspended in a suitable (named) inert vehicle such as water, gum acacia, maize oil or polyethylene glycol. Suitable precautions should be taken to ensure that operators are not exposed to the active ingredient.

Multiple-dose oral toxicity

Test procedures are similar to those described for evaluating single-dose toxicity. Typically, the test substance is administered in four to six daily doses at two or more dosage levels (EPPO, 1999). For some established multiple-dose rodenticides (e.g. warfarin), quite different results have been reported when comparing the single-dose and multiple-dose (5 day) oral LD_{50} values. For some multiple-dose rodenticides, therefore, single-dose oral LD_{50} values may provide an unrealistic picture of toxicity (Ashton *et al.*, 1987).

The multiple-dose oral LD_{50} may also provide a useful indicator when selecting the concentrations of the active ingredient in baits to use in subsequent feeding tests.

No-choice feeding tests

By far the most important rodenticide preparations are baits. A primary objective of evaluation here is to determine the free-feeding toxicity of rodenticide bait preparations (Table 7.3). Bait concentrations for novel, slow-acting poisons may be determined from multiple-dose toxicity-test mortality curves. The duration of the test should be appropriate to the proposed methods of use for that rodenticide, normally 1 or 2 days for single-dose rodenticides (fast and slow acting) and up to 6 days for multiple-dose rodenticides.

Having determined the single-dose oral LD_{50} of a rodenticide and optimized its concentration in a bait formulation, it is possible for a particular target pest of average weight to calculate the theoretical amount of bait

Table 7.4. Relative potencies, recommended concentrations and amounts needed to give an LD_{50} dose of various anticoagulant rodenticides to a Norway rat of 250 g body weight (Brookes and Rowe, 1987; acute oral LD_{50} values obtained from Tasheva, 1995).

Anticoagulant	LD_{50} (mg kg^{-1})	Bait concentration (mg kg^{-1})	LD_{50} dose as g bait (g bait/250 g rat)
Brodifacoum	0.26	50	1.3
Flocoumafen	0.46	50	2.3
Difethialone	0.56	50 (25)	2.8 (5.6)
Bromadiolone	1.125	50	5.6
Difenacoum	1.8	50	9
Diphacinone	3	50	15
Coumatetralyl	16.5	375	11
Chlorophacinone	20.5	50	102.5
Pival	50	250	50
Warfarin	58	250	58

required to deliver an LD_{50} dose (Table 7.4; Brooks and Rowe, 1987). However, theoretical potency values are only useful if it can be established that, after ingestion, the rodenticide is readily absorbed in the intestine and available at its site of action, and is not modified, bound to the food and excreted or metabolized. This property of a compound is referred to as its bioavailability. The bioavailability of a rodenticide in a particular bait formulation can be estimated in a no-choice test by comparing the actual bait LD_{50} with its theoretical value.

Choice feeding tests

However potent a rodenticide, its acceptability in a bait in the presence of competing alternative food is of critical importance. The palatability of a rodenticide is normally determined in the laboratory by comparing its consumption with that of a challenge diet of detailed specification, where there is a free choice of both. For most purposes, differences between the rodenticide and challenge baits can be analysed statistically using a paired *t*-test or analysis of variance (EPPO, 1999).

The challenge diet

The nature of the challenge diet varies considerably in different parts of the world and may have been developed for a particular group of species (e.g. the *Microtus* test diet, see below); the challenge diet may be based on a single type of grain, such as rice, wheat or maize, or may simply be a standard commercial rodent diet. The challenge diet provides the principal criterion on which palatability determinations are based and is, therefore, a critical component of a reliable and reproducible test. In addition, an important quality of a challenge diet is the constancy of its palatability, particularly during storage from the time of manufacture to its eventual use. Examples of the variability of the challenge diet as suggested by the EPPO guidelines and the US EPA are outlined below.

The EPPO guidelines provide a basic plain bait recipe for use in palatability tests based around an unspecified cereal grain, and consisting of:

- coarsely cut cereal, 90%;
- maize oil, 5%; and
- whole wheat flour (or medium ground oatmeal), 5%.

The principal challenge diets adopted by the EPA are the following:

1. *Microtus* test diet for non-commensal species that infest agriculture, such as squirrels and microtine or cricetid rodents:

- ground rolled oats, 50%; and
- ground commercial rodent diet, 50%.

2. Standard EPA meal for commensal rodents (Norway rat, roof rat and house mouse):

- cornmeal (whole yellow ground maize), 65%*;
- rolled oat groats (ground), 25%*;
- sugar (95% purity), 5%; and
- maize oil (95% purity), 5%.

The asterisks (*) indicate that particle size distribution is specified by retention through two sieve sizes.

To illustrate some of the problems associated with the laboratory evaluation of palatability, our experience with the use of standard EPA meal will be described. This challenge diet was originally selected because of its perceived intermediate palatability among the candidates screened and it was, therefore, considered a good representative for natural food sources in a range of infestation types.

According to EPA guidelines (US EPA, 1982), the standard meal should be prepared according to a detailed methodology, which specifies:

- quality of the materials;
- particle size distribution of the cornmeal;
- particle size distribution of the ground rolled oat groats;
- methods of storage of the prepared meal; and
- maximum period of storage (frozen for 6 months).

In tests carried out at the University of Reading in the UK, it was found that batches of standard meal prepared according to EPA guidelines did not have a consistent and stable palatability. Although care was exercised to ensure adherence to EPA methods of preparation, a marked decline in palatability was observed over the initial 10 week storage period. Liberation of a pleasant aroma following grinding to produce the required particle-size specifications is thought to be responsible for an initial short-term enhancement in palatability of the challenge diet. Such variability was not acceptable, because an important expectation of a challenge diet is the consistency of its palatability. If grinding is necessary to generate a specified cereal particle size, a period of storage may be required to remove any short-term enhancement of palatability. With the introduction of each new batch of challenge diet, any between-batch variations in palatability should always be determined by a choice test between the successive batches.

Differences also occur between recommended methods of presentation of the test and challenge diets. The EPA, EPPO and BPD guidelines recommend interchanging the positions of the test and challenge diets on a daily basis, but where EPA recommends simple replenishment of food bowls, the BPD recommends discarding the used bait and refilling with a fresh supply, and EPPO advocates the replacement of diets using clean bowls.

The test period

In addition, the international guidelines are not consistent on the required duration of the test period in choice feeding tests (Table 7.5), and consumption of a rodenticide bait can be very variable during this period. To illustrate this point, food consumption data obtained from palatability tests at the University of Reading using Sprague Dawley Norway rats have been analysed over the conditioning and test periods, and are reported in the next section.

Table 7.5. Duration of the test period (days) in choice feeding tests.

	US EPA (1982)		EPPO (1999)		BPD (EU, 2009)	
Speed of action	Single feed	Multiple feed	Single feed	Multiple feed	Single feed	Multiple feed
Fast (acute)	1–2	–	1	–	Not considered	–
Fast (chronic)	3	–	1–2	–	4 (3–5)	4 (3–5)
Slow (chronic)	3	15	4	4+	4 (3–5)	4 (3–5)

Neophobic avoidance of rodenticide formulations on the first day of test

During conditioning, singly caged animals were presented with ground laboratory diet in two bowls symmetrically placed at one end of the test cage. During the test period, the ground laboratory diet was replaced in one bowl by standard EPA meal, and in the other bowl by the test rodenticide (or by a different batch of EPA meal in tests comparing EPA palatability). Each day, the bowls were removed, weighed, replenished, reweighed and replaced in the test cage, and the positions of the two bowls were interchanged.

In tests comparing the palatability of different batches of EPA meal, the transition from ground laboratory diet to EPA meal corresponded with a significant increase in total consumption (Fig. 7.1). In tests where rats were presented with either a wax-block formulation or a pellet formulation against EPA meal, acceptance values were significantly lower on the first day than on the second and subsequent days of test (Fig. 7.2).

As total consumption did not decrease on transition from the conditioning to test diet when comparing the palatability of different batches of EPA meal, it appears that the reduced acceptance values for wax-block and pellet formulations on day one of the test represent a neophobic response to these formulations. This aspect of testing requires further study, with consideration of the form and texture of the conditioning diet on the initial acceptance of the test bait.

Single-feed slow-acting rodenticides: evidence of toxicosis by day 4 of test

In palatability tests performed at the University of Reading, when the test material is a rodenticide (normally a second-generation anticoagulant), total food consumption usually peaks on the first day of the test and falls to a minimum by test day 4. The initial peak is thought to reflect the low palatability of the conditioning diet (ground laboratory diet). Analysis of total food consumption revealed a significant reduction from test day 3 to test day 4, and is considered to be a result of the animals suffering toxicosis. Such animals are unlikely to be so discerning in their appraisal of rodenticide palatability. For palatability tests on single-feed anticoagulant rodenticides, therefore, a 3 day test would be more appropriate.

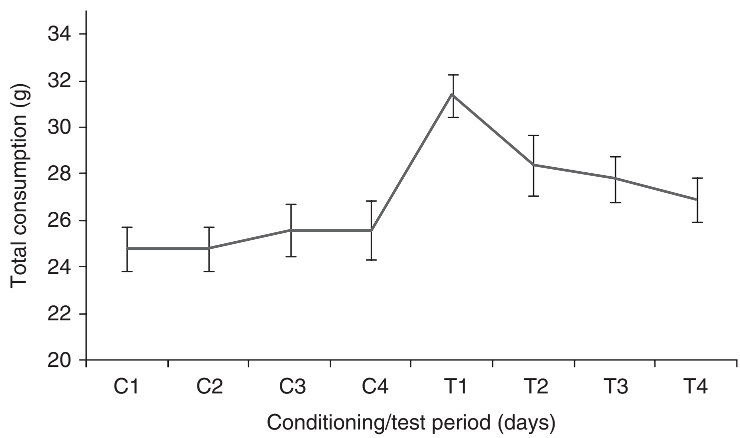

Fig. 7.1. Total daily consumption by Sprague Dawley rats over a 4 day conditioning period (where a ground laboratory diet was available) and over the 4 days of test, in which the animals were given the choice of two batches of standard US EPA meal. Values represent the means from 50 male and 50 female test animals (±SE).

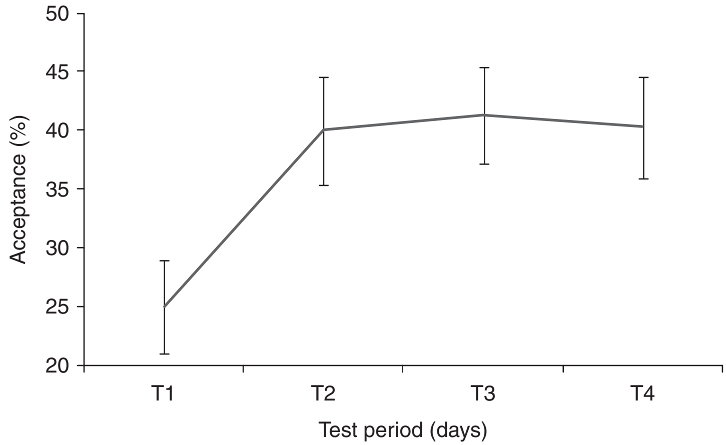

Fig. 7.2. Acceptance of a pelleted anticoagulant formulation (versus standard US EPA meal) calculated on the basis of consumption on either test day 1, test day 2, test day 3 or test day 4, using Sprague Dawley rats. Values represent the means from 35 male and 35 female test animals (±SE).

Interpretation of the results of choice feeding tests

The results of choice tests can be expressed in one of two ways (see equations at the bottom of the page):

Bait acceptance uses a finite scale of 0–100%, whereas the palatability ratio is an asymmetric scale ranging from zero to infinity, around the neutral preference level of 1.0. For statistical purposes, because of this asymmetry, it may often be appropriate to work with the log transformation of the palatability ratio, log (T/C) = log T – log C (or perhaps log (T + 1) – log (C + 1) to allow for cases where either T or C is zero).

Some government authorities have specific, if arbitrary, palatability requirements that a proposed bait formulation must satisfy. For example, the EPA requires that anticoagulant rodenticides achieve 90% mortality, and an acceptance level that statistically is not significantly less than 33% when tested against their standard diet (equivalent to a palatability ratio of 0.5). The 33% acceptance was initially developed for first-generation anticoagulant rodenticides, and its application to the more potent second-generation anticoagulants is due in part to regulatory inertia. This rather simplistic approach to evaluating the palatability of a particular bait formulation fails to take into account wide variation in the potencies of slow-acting rodenticides (Table 7.4).

The EPA currently has a series of efficacy test requirements for the registration of rodenticide baits against the three commensal species, the house mouse, Norway rat and roof rat (US EPA, 1982: Draft Laboratory Test Methods, OPP (Office of Pesticide Programs) Designations) (see Table 7.6.a.).

- For anticoagulant dry baits, following a 15 day choice against standard EPA meal, acceptance should not be less

$$\text{Bait acceptance} = \frac{\text{total weight (g) of rodenticide bait eaten (T)}}{\text{total weight (g) of control bait (C) and rodenticide bait (T) eaten}} \times 100$$

or

$$\text{Palatability ratio} = \frac{\text{total weight (g) of rodenticide bait eaten (T)}}{\text{total weight (g) of control bait (C)}}$$

Table 7.6. Efficacy requirement for rodenticide formulation registration (US EPA, 1982; EU, 2009).

(a) EPA

Test	OPP designation[a]	Species	Test (days)	Acceptance	Mortality
Anticoagulant dry bait	1.203	Norway/roof rat	15	Not significantly less than 33%	≥90%
	1.204	House mouse			
Acute dry bait[a]	1.209	Norway/roof rat	1 or 2	(Not specified)	≥90%
	1.210	House mouse			
Anticoagulant wax block and wax pellet	1.213	Norway rat	15	33% (fresh bait)	≥90%
	1.214	Norway rat		25% (weathered bait)[b]	≥80%
Anticoagulant wax block and wax pellet	1.213	House mouse	15	33% (fresh bait)	≥90%
	1.214	House mouse		25% (weathered bait)[b]	≥80%
Anticoagulant place-pack dry bait	1.217	Norway/roof rat	15	(Not specified)	≥90%
	1.218	House mouse			≥90%

(b) EU (guidance for house mice, Norway rats and roof rats)

Feeding test	Mode of action	Test period (days)	Age	Acceptance	Mortality	Active ingredient
Mortality	Acute	1	Fresh	n/a	≥90%	Novel
Mortality	Chronic	3–21	Fresh	n/a	≥90%	Novel
Bait choice	All	4 (3–5)	Fresh	≥20%	≥90%	Novel and known
Bait choice	All	4 (3–5)	Aged[b,c]	≥20%	≥90%	Novel and known

[a]Under the EPA's Office of Pesticide Programs (OPP) designations, single feed claim for anticoagulant baits must use a 1 day bait exposure period.
[b]For claims that bait is effective in wet or damp areas, 'weathered' formulations must be used that have been subjected to 90–100% relative humidity at a temperature of approximately 100°F (37.8°C) for approximately 15 days.
[c]An aged formulation will have been stored for a stated period before the test (i.e. for 2 years) or, alternatively, will be subjected to 'accelerated ageing' by being stored under challenging conditions (for instance: relative humidity >60% and temperature >25°C).

than 33% and mortality should not be less than 90% (for all three commensal species).
- For acute dry baits, following a 1- or 2-day choice test against standard EPA meal, mortality should not be less than 90% (with no acceptance requirement). For anticoagulants to make the 'single-feed' claim, they must achieve at least 90% mortality following the 1-day choice test (for all three commensal species).
- For anticoagulant wax-block and wax-pellet formulations to be effective in dry areas, following a 15 day choice against standard EPA meal, acceptance should not be less than 33% and mortality should not be less than 90% (for Norway rats and house mice).
- For anticoagulant wax-block and wax-pellet formulations that claim to be effective in wet or damp areas, following a 15 day choice against standard EPA meal, mortality should not be less than 90%, and acceptance should not be less than 25%; where the formulation tested has been subjected to 90–100% humidity at a temperature of approximately 100°F (37.8°C) for approximately 15 days (for Norway rats and house mice).
- For anticoagulant place-pack dry bait, following a 15 day choice test against standard EPA meal, mortality should not be less than 90% (with no acceptance requirement) (and for all three commensal species).

In Europe, the Technical Notes for Guidance on Product Evaluation (Product Type 14 – Rodenticidal Biocidal Product) of the BPD (EU, 2009) provide an overview of rodenticide efficacy assessments that can be used against house mice, Norway rats and roof rats, to ensure that only effective products enter the Market (see Table 7.6b). For new active ingredients, there is a requirement to demonstrate the lethal effect of the product, and this can be achieved using mortality feeding tests, where the no-choice feeding periods for rodenticides with acute and chronic modes of action are 1 day and between 3 and 21 days, respectively. For new and existing active ingredients, there is also a requirement to assess the palatability of the product, and this is achieved using the bait choice feeding test, where test animals are presented with the free-feeding choice of the test product and a challenge diet over a test feeding period of between 3 and 5 days, although this is considered 'most suited to slow acting toxicants' (EU, 2009).

According to the Technical Notes for Guidance, rodenticides are considered to be efficacious if they satisfy three criteria, two of which are assessed in the laboratory:

- In the mortality feeding test, the percentage of dead animals should not be less than 90%.
- In the bait choice feeding test, the percentage of ingested bait containing the rodenticide product (the acceptance) should not be less than 20%; with the following exception. For tests where there is mortality in at least 90% of test animals, a lower level than 20% of the total food consumption is acceptable.
- In 'field' trials or 'semi-field' trials, the method of assessment used for monitoring the test population (i.e. rodenticide bait take, census bait take, tracking activity, etc.) should indicate a minimum of 90% reduction in the assessment score.

For formulations containing a new active ingredient, if mortality of at least 90% of test animals is achieved in the bait choice feeding test, there would be no requirement to conduct a mortality feeding test.

Laboratory measurements of palatability and bait acceptance only give an indication of the likely performance of a formulation in the field, and require careful interpretation. Unfortunately, there is a lack of published information comparing laboratory-generated data with actual field performance.

Tests on Groups of Rodents in Rooms or Pens

Behavioural interactions between wild rodents are influenced by a wide range of factors involving social status (including age, sex and social ranking), physical environment (including temperature, humidity and light regime) and availability of food, water, shelter and free-living space. Accordingly, animals housed within the confines of a small test cage do not provide a good model for behavioural studies.

The establishment of social groups of rodents within an enclosed area has provided a useful opportunity to study social interactions, and to observe the effects of manipulating their environment. Enclosure studies can also be considered an intermediate step between cage tests and field trials, and for house mice in particular, are sometimes considered a suitable alternative to the latter.

In confined colonies of wild Norway rats in large outdoor enclosures, the control of environmental factors can be difficult (Calhoun, 1963). In such an environment, detailed behavioural monitoring can also be problematic. Small indoor 'single room' enclosures allow much greater control of environmental conditions, are better suited for observations and are useful for tests on colonies of mice (Rowe and Bradfield, 1977; Rowe *et al.*, 1985). However, in prolonged tests with Norway rats, the rapid development of a high population density will commonly lead to abnormal patterns of behaviour (Calhoun, 1962). A small colony of Norway rats housed in a large arena therefore offers the best compromise between the need for experimental control and relevance to the natural situation (Shepherd and Inglis, 1987).

Maintaining equal numbers of both sexes in a pen is often difficult. Males can be extremely aggressive and often fight, so it is important to provide sufficient harbourage for all animals. Animals that die before the test as a result of fighting may be difficult to replace, with the replacement animals being treated as an intruder by the established group. The use of laboratory-bred F_1 offspring of wild-caught parents that have been raised together as siblings will reduce problems of aggression (Kaukeinen, 1988).

Measurement of food consumption may be assisted by taking steps to reduce and collect spillage (i.e. the use of large trays beneath food containers). On each day of weighing, it is necessary to survey the enclosure, including harbourages, for scattered diet, particularly where bait-block formulations are under test.

Test methods for rodenticide evaluation using confined colonies of rodents are included in both the EPA (Palmateer, 1979) and EPPO (1999) guidelines.

Confined colonies of wild mice

Suitable field trial sites for the evaluation of rodenticide preparations against mice are often difficult to locate. As mice have a generally restricted foraging territory, pen trials offer an attractive alternative to field assessments.

The former UK Ministry of Agriculture, Fisheries and Food (MAFF, now Defra) used confined colonies of wild mice to provide post-laboratory information on rodenticide application techniques before these were examined under field conditions (Rowe and Bradfield, 1977). Trials were conducted within rectangular metal pens measuring 9.5 × 2.5 m (Rowe *et al.*, 1985). Mice were allowed to range freely in the pen for at least 7 days before the initiation of a baiting trial. Two staple foods and water were provided ad libitum, located near the breeding cage. During the test period, rodenticide bait was placed at eight sites outside the nesting area of the pen and the consumption of rodenticide and non-toxic diet was measured daily, typically over a 21 day test period.

In contrast, the German Federal Environment Agency (Umweltbundesamt or UBA) used enclosures with a floor area of 5 m^2 to confine wild strains of house mice obtained from laboratory colonies (Schmolz, 2011). They conducted efficacy no-choice and choice tests using groups of mice (of between 15 and 27 individuals with a male to female ratio of between 1:1 and 1:2), with test periods of 21 days for no-choice tests and 28 days for choice tests.

Confined colonies of wild rats

In general, field trials are the preferred option for Norway rats since infested sites are usually readily available. However, confined colonies of rats can provide useful and detailed information concerning rodenticide evaluation, particularly with respect to behavioural interactions between individuals.

The former MAFF Central Science Laboratories (CSL, now Fera) erected two rodent observation arenas, each 5 m × 10 m, within a large, bird-proofed agricultural building (Shepherd and Inglis, 1987). The floors of the arena were concrete and the rats lived in nest boxes built within straw bales. There was a raised observation hut that overlooked both arenas. Two feeding stations within each arena were erected on electronic balances, which were continuously monitored by a microcomputer. In addition to food consumption, it was often possible to obtain a measure of body weight that could allow individual identification when rat numbers were small.

Freeze branding the original colonizers and the examination of video recordings provided additional information on individuals, which was particularly useful when there was more than one animal at the feeding station. Similarly, transponder tags implanted under the skin were monitored by devices mounted in the feeding stations or nest boxes, but there was a problem with the identification of young rats born in the arena during a test.

In relation to rodenticide evaluation, the arenas were used to gather information on:

- circadian feeding patterns;
- social interactions while feeding;
- consumption data for different age and sex classes;
- relative palatability of different bait formulations;
- bait shyness; and
- neophobia.

The arenas could also be linked by a connecting tube, thus enabling the investigation of:

- interactions between two established rat populations; and
- invasion of an established rat population into an area containing a preferred or novel food.

The UBA used wild strains of the Norway rat and roof rat that were obtained from laboratory colonies, and conducted efficacy no-choice and choice tests using groups of rats (of between five and ten individuals with a sex ratio of between 1:2 and 2:1) in enclosures with a floor area of 6 m^2 (Schmolz, 2011). The duration of the no-choice test was 10 days for Norway rats and 21 days for roof rats; and the duration of the choice test was 14 days for Norway rats and 28 days for roof rats.

Humaneness

In the UK, the Food and Environment Protection Act 1985 (FEPA) and Control of Pesticides Regulations 1986 (COPR) legislation require that pests should be controlled using methods that are humane. In addition, a recent EU Directive (91/414/EEC) requires that vertebrate pesticides do not cause undue suffering. Humaneness is an ambiguous term that is difficult to define, but infers the minimization of pain, distress and discomfort during the killing of animals through control programmes (see Chapter 15).

The *Data Requirements Handbook* (UK HSE, 2012), which is published online by the UK Health and Safety Executive (HSE), outlines a strategy in which data on humaneness are developed to support applications for pesticide registration made to the Chemicals Regulation Directorate (CRD) for approval of agricultural, horticultural and home garden pesticides (also known as plant protection products). Chapter 9 of the handbook, entitled 'Humaneness for Vertebrate Control Agents', proposes a two-stage strategy in which a literature search is first conducted by the applicant. Available data derived from the search are to be presented to the HSE, such as time of first occurrence of signs of toxicity, the nature, severity and duration of the signs observed, time to insensibility, time to death and results of any post-mortem examinations. The second stage of animal testing may begin after these data have been considered and in consultation with HSE.

Assessing the degree of pain and suffering

The assessment of the degree of pain and suffering is subjective and cannot be measured directly. For example, phenomena often associated with pain, such as raised blood pressure and altered respiratory depth, can occur in animals following destruction of the cerebral cortex. Consequently, physiological data should be assessed in the light of behavioural information.

A detailed descriptive account of the animal before, during and after exposure to the compound may reveal behavioural and physiological changes that can be used to assess the degree of pain and suffering. The timing of observations will be critical and should be performed at a similar frequency before and throughout the course of the trial; the observer should also be familiar with the normal appearance, performance and behaviour of the animal prior to the start of the trial.

With any vertebrate toxicant, its effect on the rodent in the field is likely to be inhumane, as a result of the combined effects of the symptoms of toxicity, the time period from onset of symptoms to death and the inability of affected animals to defend themselves adequately from conspecifics and predators.

Following the consumption of a lethal dose of a fast-acting rodenticide, the onset of symptoms is rapid, and the effect on the rodent is often extreme. It is not surprising that the rapid development of such extreme symptoms will induce conditioned bait aversion in the target species. For example (John Greaves, personal communication):

- Fluoroacetamide – causes intermittent convulsions after 2 h and death within 2 days.
- Sodium fluoroacetate – causes intermittent convulsions after 30 min and death within 2 days.
- Norbormide – causes terminal convulsions after 15 min and death from 30 min to 24 h.
- Zinc phosphide – causes terminal convulsions within 30 mins (which may continue for several hours), but death may be delayed for 3 or more days. Symptoms include abnormal posture, wild running and biting, and prostration.

With alphachloralose, symptoms begin after 5–20 min, and may include loss of motor coordination and agitated wild or convulsive behaviour before prostration and torpor set in. Despite the alarming appearance of the symptoms, alphachloralose is considered humane in view of its recorded use as a human anaesthetic.

With slow-acting rodenticides, time to death is delayed, raising concerns about prolonged suffering of the target rodent. For example:

- The anticoagulants: these cause reduced blood clotting ability after as little as 24 h, leading to death in 3–12 days after consumption of a lethal dose. Illness is often short, quiet and uneventful, but symptoms causing prolonged suffering (subcutaneous bleeding, respiratory distress, etc.) are not uncommon and may last for some time (typically less than 3 days).
- Calciferol: this causes irreversible calcification of the soft tissues, including the coronary arteries. Symptoms develop around day 2, with death usually within a week. They can include hind leg paralysis.
- Bromethalin: this uncouples oxidative phosphorylation in the mitochondria. Symptoms develop within 24 h, with death usually within 2–4 days. Symptoms can include convulsions, tremors and hind leg paralysis.

It is very difficult to make meaningful objective humaneness assessments when vertebrate toxicants with different modes of action have such contrasting effects. Two questions that arise are:

- Is it preferable for the target species to die quickly after consumption of a lethal dose, despite the severity of the symptoms, or is it preferable for the animals to experience less extreme symptoms over a longer time period?
- From an animal welfare point of view, is it sufficient to assess the humaneness of rodenticide active ingredients by monitoring their effect on members of the target species that have been provided with a lethal dose in a laboratory

environment? In the field situation, such a situation will only occur where the rodenticide has been applied optimally and against a target species that is fully susceptible to the rodenticide.

For the acute rodenticides, the most effective rodenticide treatment in the field is unlikely to achieve more than 70% control, with surviving animals developing conditioned bait aversion after recovering from significant symptoms of toxicity.

Many anticoagulant rodenticides are unable to control populations of rodents effectively because of geographically widespread levels of physiological resistance. In such situations, a proportion of the target species are controlled by the anticoagulant, but the majority of animals survive, and evidence from the laboratory would suggest that they develop symptoms of toxicity, stop feeding, recover and then start feeding again (Quy *et al.*, 1995; Hussain, 1998).

Might it be more meaningful then to consider humaneness in terms of a rodent-control procedure, rather than for each rodenticide active ingredient? Humaneness might best be served by achieving effective and rapid control of the target population; typically, this would involve integrated pest management strategies potentially involving a number of rodenticide active ingredients. Ineffective control will not only result in the development of sublethal effects in significant numbers of target animals, it will also prolong the treatment, thus increasing exposure to non-target species and introducing additional humaneness considerations.

Conclusion

Much of the considerable effort involving the laboratory evaluation of rodenticides is aimed at meeting the increasing demands of various regulatory bodies. Attempts are being made to harmonize the approach to rodenticide evaluation with the intention of promoting the scientific aspects of testing. Although it is accepted that it is not possible to devise standard test methods appropriate for all rodenticides and target species, the existing guidelines represent an agreed basic approach that, as a result of experience, serves as a foundation for future development and refinement.

Examples of areas requiring further harmonization include the species used, their maintenance and palatability studies. For commensal species in particular, the selection of a challenge diet with a consistent palatability that does not require complex manufacturing procedures would improve the quality of the data generated, thereby increasing the reliability of the test procedure, and allowing realistic comparisons between formulations. To this end, the use of a ground laboratory diet as the challenge diet has much to commend it.

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8 Field Evaluation of Rodenticides

D.P. Cowan and M.G. Townsend
National Wildlife Management Centre,
Animal Health and Veterinary Laboratories Agency (AHVLA),
Sand Hutton, York, UK

Introduction

Why do we need to devise methodologies to evaluate the effectiveness of rodenticides? First, both users and manufacturers require objective scientific data in order to make appropriate practical and commercial decisions. Secondly, rodenticides are toxic and are thus subject to government regulation in many parts of the world. Effectiveness is only one part of these regulatory controls, along with issues such as risk to humans and other non-target species, and humaneness. Nevertheless, if a rodenticide material lacks its intended utility consideration, neither of these other concerns becomes unnecessary.

The only certain way to assess the practical value of a rodenticide is to evaluate its performance under field conditions. The diversity of circumstances in which rodenticides are used, from the control of commensal rodents in sewers to the reduction of field rodent populations, together with the variety of available materials, has yielded a substantial literature on field evaluation. Yet this same diversity often renders comparison between studies difficult, and the necessary constraints on making extrapolations from one set of circumstances to another may not be fully recognized. There have been a number of attempts to establish standard methods for field evaluation, notably in Europe by the European and Mediterranean Plant Protection Organization (e.g. EPPO, 1975, 1998), by the European Union (EU) with respect to implementation of Directive 98/8/EC concerning the placing of biocidal products on the market (EU, 2009), and in the USA through the Environmental Protection Agency (US EPA) and regulation by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (e.g. Peardon, 1977; Jacobs, 2011). Although such guidelines have been useful in establishing the criteria relevant to different circumstances, there is still some way to go before the benefits of standardized methodologies can be fully realized, in terms of avoiding unnecessary duplication and attaining a better understanding of the factors influencing rodenticide performance. This chapter aims to clarify the issues involved in establishing standard methods for the field evaluation of rodenticides.

Evaluation Criteria

Any standard methodology must incorporate a clearly defined currency in which the outcome of control treatments is measured. The ultimate currency might be the extent to which the problems caused by the species concerned are alleviated. Damage assessment is valuable for evaluating field rodenticide performance (see Chapter 10), and surveys of damage may well be the most appropriate means of evaluating large-scale rodent-control programmes (e.g. Richards and Buckle, 1987). However, the damage recorded may not always be ascribed with confidence wholly to the target species because of complex interactions between a variety of pests and diseases. Such interactive effects make it difficult to evaluate performance at the level of individual control, particularly for commensal rodents (see Chapter 2).

Many difficulties can be overcome by evaluating the efficacy of treatments in terms of change in size of the target population. Treatment efficacy should not be confused with efficiency. The latter incorporates some form of assessment of both costs and benefits. At one level, efficiency could be considered as the measurement of the relative efficacy of treatments with varying costs; if there is no difference in efficacy then the cheapest treatment must be the most 'efficient' (Greaves *et al.*, 1988). At another level, the costs of damage might be incorporated such that if the relationship between rodent numbers and damage is known, along with the average efficacy and treatment cost, and the rate of recovery of the rodent populations concerned, then the net financial consequences of such treatments can be calculated (Salmon and Lickliter, 1983). This approach has met with some success in a variety of contexts for the development of control strategies. In the future, measurement of rodenticide efficiency will increasingly need to incorporate both risk assessment of hazards to non-target species (see Chapter 16), and considerations of humaneness (see Chapter 15) in the balance between the costs and benefits of treatments that represent efficiency. Treatment efficacy is, nevertheless, an essential prerequisite of efficiency.

Measuring Efficacy

There are two approaches to measuring the ability of a rodenticide to affect changes in population size: longitudinal evaluation and census evaluation.

Longitudinal evaluation

A longitudinal study follows the fates of a sample of known individuals supposed to be representative of the target population alive at the beginning of the treatment. Efficacy is measured as the proportion of this sample that subsequently succumbs to the rodenticide. It has only been possible to monitor individual rodents in the field satisfactorily since the advent of radio-telemetry and the increasing availability of small transmitters, including the recent advent of GPS (geographical positioning system) collars light enough to allow their attachment to rats.

A possible source of bias from this approach is that animals fitted with telemetry systems might be unrepresentative. The age and sex structure of the sample are particularly subject to bias given that live capture methods are often more successful with animals of a particular age or sex. Sex differences in susceptibility to rodenticides or age-specific effects (e.g. Salmon and Marsh, 1979) will lead to error in estimates of efficacy extrapolated from a biased sample relative to the entire population.

A more disturbing potential source of bias might arise from individual variation in behaviour. Traps are more likely to catch the less cautious, more active or more wide-ranging individuals, often the behaviourally subordinate animals, which are also more likely to locate and consume rodenticide than individuals with more conservative behaviours (Shepherd and Inglis, 1987). Similarly, animals of subordinate status might be more likely to be captured and also be more susceptible to the treatment than more dominant individuals. A partial solution is to use a variety of live capture methods to obtain the population sample. These might include the use of both baited and unbaited 'blunder-in' traps, stopped snares and nets. For burrowing species, the use of ferrets to bolt animals from their refuges into nets can be considered (Cowan, 1984).

Telemetry techniques enable evaluation of individual home ranges for the duration of the treatment (White and Garrott, 1990: Buckle *et al.*, 1997). Hence, survival due to home range shift outside the treated area can be discriminated from survival in the context of continuous exposure to the treatment (Lambert *et al.*, 2008). Furthermore, radio transmitters facilitate the recovery of the bodies of animals that die during the course of the treatment. Dead animals can be recognized by using temperature-sensitive transmitters whose pulse length or frequency changes as a dead body cools. Autopsy of the bodies that have been recovered may allow the discrimination of deaths attributable to the rodenticide from those due to other causes (Cowan *et al.*, 2003). However, the apparent disappearance of animals during the course of a treatment cannot necessarily be attributed to the effects of the rodenticide. Transmitters can fail or become detached, or animals may emigrate undetected away from the study site. Alternatively, animals may succumb to the treatment but be carried away by predators or scavengers with or without the transmitter attached.

Census evaluation

The most commonly used method of measuring efficacy is to make at least two estimates of population size (so-called 'censuses'), one at the beginning of the treatment and one at the end. Efficacy is measured as apparent change in population size, generally expressed as a proportion or percentage of the initial population size. Natural rodent populations, though, fluctuate during the course of a treatment through causes other than the rodenticide. On the one hand, this offers the opportunity to measure the real practical utility of the treatment against naturally fluctuating populations. On the other hand, these additional sources of variation may obscure changes in population size arising from the treatment and confound studies of comparative efficacy. Dealing with these issues is a matter of experimental design rather than a function of the methods used to obtain estimates of population size, which fall into two categories: direct and indirect census methods (Kaukeinen, 1984).

Direct census methods

A direct census seeks to obtain an estimate of absolute population size. The classical approach for rodent studies is to use a capture–mark–recapture (CMR) technique. Methods of marking rodents have been extensively reviewed by Taylor and Quy (1973). Subsequently to that review, the range of available methods has expanded to include the use of passive integrated transponders (PIT) tags (Quy and Cowan, 1996) and injection with tattoo ink (Petit *et al.*, 2012). The simplest estimate of population size is the Petersen or Lincoln index, which uses the number of individuals in an initial population sample that are marked and released (m_1), the number of marked animals in a subsequent population sample (m_2) and the size of the second population sample (n_2). Thus:

$$\text{Estimated population size} = \frac{m_1 \times n_2}{m_2} \quad (8.1)$$

Mice are usually easier to trap than rats, and Quy *et al.* (2009) demonstrated that this form of CMR provides a comparatively accurate assessment of house mouse numbers. The method is, however, time-consuming and would not therefore be universally practicable or cost-effective for many studies, particularly where data on individual animals are not required, as will be the case for most efficacy studies. More sophisticated variants of this basic theme allow many implicit assumptions to be tested and, in some cases, allowed for in the analyses (White and Garrott, 1990). Public domain software is available for undertaking these analyses (White and Burnham, 1999). Heiberg *et al.* (2012) demonstrated the use of this approach to estimate Norway rat (*Rattus norvegicus*) populations in sewers, but such methods generally require a population sampling regime whose timescale is incompatible with experimental designs for studying rodenticide efficacy.

The assumption that all individuals in the study population are equally trappable is unlikely to be met except for small rodents living in relatively homogeneous open-field habitats. The use of CMR on a trapping grid using small mammal traps has been advocated for studies of *Microtus agrestis*, the field vole, in Europe (Myllymäki, 1970). The grid system may be varied to apply the equivalent number of traps in the most appropriate locations, e.g. runways for *M. arvalis*, the common vole (EPPO, 1975). Other authors still consider the limitations of CMR to be such that it is inappropriate even for some small rodents in open-field habitats.

An alternative direct census approach to CMR is to use trapping to derive the minimum number alive (MNA), which is defined as the number of individuals caught in a capture session, plus those that were not caught at that time but were caught both previously and subsequently (Krebs, 1966). The use of MNA has been justified by claiming that its assumptions are minimal compared with those of statistical estimators (Hanley and Barnard, 1999) – although this is not necessarily the case, as the MNA approach has a number of potential inherent biases (Pocock *et al.*, 2004).

Indirect census methods

Indirect methods rely on measuring changes in aspects of rodent activity that are supposed to reflect changes in rodent population size. The simplicity, cost and limited duration of indirect methods have led to their dominant role in evaluating efficacy. The ideal indirect census method should not alter the behaviour of the animals concerned, but it should be linearly related to population size and species specific so that measurement of the activity of the target species is not confounded with that of others. Some of the more commonly used methods are described below, with practical guidelines.

TRAPPING. The distribution of traps needs to take into account the behaviour of the target species. Specifically, for all members of the target population to have some probability of capture, the maximum spacing between traps should not exceed the minimum known home range.

For small field rodents, traps are often set on uniform grids or along transects. A special case of the transect approach is to place traps along a habitat boundary, such as a field edge, if the target species is known repeatedly to cross this boundary when moving between refuge areas and a food supply. The most appropriate method for commensal rodents living in heterogeneous habitats is to distribute traps at a predetermined density, but with each trap being placed with reference to signs of rodent activity, such as runways or burrows. In order to obtain comparable pretreatment and post-treatment indices, the density and dispersion of traps should be consistent. Some authors have argued that traps should be relocated between the two census periods, in order to overcome perceived problems of increased trap shyness (Peardon, 1977), but others consider that this procedure confounds the equivalence of the two indices. Live trapping can provide useful data, especially for small species such as *Mus* spp. (mice) and *Microtus* spp. (voles), but for larger rodents it tends to be expensive and labour intensive relative to alternative census methods, while offering no particular advantages. An exception is where it is desirable to monitor specific biological parameters in relation to the rodenticide involved; for instance, the prevalence of physiological resistance to the rodenticide (Cowan *et al.*, 1995).

Censuses derived from kill trapping are generally of limited value in providing comparative pretreatment and post-treatment indices of population size unless the population density is sufficiently high to allow a sample to be removed without a marked effect on that density (e.g. Myllymäki *et al.*, 1971). However, kill trapping can provide a useful minimum estimate of the absolute numbers of rodents present at the end of a treatment. The US EPA guidelines for the evaluation of rodenticides against commensal species require 3 days of snap trapping to be performed with one trap set for each bait point used during the treatment (Spaulding and Jackson, 1983).

VISUAL COUNTS. Visual counts can be particularly useful for larger species (Poole *et al.*, 2003). Variation in terrain and thus visibility generally make visual counts unreliable in terms of size comparisons between populations. Clearly diurnal counts of a nocturnal species are of limited value. Similarly, individual variation in patterns of activity, for instance with respect to age and sex, need to be considered especially in relation to similar differences in susceptibility to the treatment. The interval between the pretreatment and post-treatment counts, i.e. the duration of the treatment, can confound comparison if this interval covers seasonal variation in behaviour or visibility (Matschke, 1984). Variation can be minimized by making counts at the same time of day and using the same observer. There are two basic approaches to visual counts. First, a defined area can be scanned from a fixed position such as an observation hide. This is probably most appropriate for diurnal species. The second alternative is to establish a predetermined transect route. This is most appropriate for nocturnal species (e.g. Taylor *et al.*, 1981). Nocturnal observations are often aided by the use of spotlights or image-intensifying equipment ('night sights') which minimize disturbance. Variation between counts can be expected according to the weather conditions. Common sense dictates that particularly adverse conditions should be avoided, but even then, experience suggests that at least three separate counts will be required to obtain a single index value.

Increasingly sophisticated time-lapse photography and video recording equipment is available that can be used to make visual counts with the minimum of disturbance. A variety of mechanical, photoelectric, ultrasonic and infrared activity-monitoring systems have been proposed over the years (Kaukeinen, 1984). In general, though, these developments have been associated with answering scientific questions over and above that of efficacy measurement. Hence, such techniques have not been incorporated into the mainstream of rodenticide evaluation, although their value should not be overlooked for specific circumstances where the assumptions implicit in less sophisticated methods are seriously violated. For instance, the detection of small mammals by motion-sensitive camera 'trapping' has become increasingly used in small mammal surveys, e.g. De Bondi *et al.* (2010). Rowcliffe *et al.* (2008) developed a method of population density estimation by camera trapping without the need for individual recognition. The estimate is derived from the camera trapping rate, the speed of movement of the target species, and the detection distance of the species by the camera sensor. This method assumes that animals move randomly and independently of one another and that cameras are placed randomly, but these assumptions may be difficult to meet for commensal rodents, in particular.

SIGNS. The variety of signs that rodents leave behind during the course of their daily activities offer considerable opportunities for devising activity indices. Counts of burrows may correlate well with numbers within a population even though changes in the number of burrows arising from changes in population size will usually take place on a longer timescale than the typical rodenticide treatment. A more useful approach is to measure changes in the number of active burrows. Here, burrows are closed with soil or plugged with other material at the beginning of the treatment and the number reopened at the end taken to be the final level of activity (Jackson, 1979). This method has been successfully used to monitor control operations on commensal rodents in urban situations, where other activity assessment methods are inappropriate. A drawback is the assumption that the entire target population is living in burrows, which may not be the case. Other forms of burrowing activity can also be useful in rodenticide evaluation, for instance counts of mounds made by fossorial species such as *Thomomys* spp., pocket gophers (Anthony and Barnes, 1983), or opening of breathing holes in snow by *M. agrestis* (Myllymäki, 1970).

Dropping counts can be used as indices of activity where there is a need to discriminate between species (Huson and Davis, 1980). Counts of droppings represent one of the few methods available for evaluating rodenticide efficacy in sewers. Given the variability in the rates at which droppings disintegrate in different circumstances, it is advisable to clear predetermined areas of droppings and count new pellets that accumulate during a given unit of time, or else use dropping boards (Emlen *et al.*, 1956).

TRACKS. Rodents leave tracks and trails in many substrates that often allow discrimination of species at least in terms of gross size, e.g. *Mus* spp. from *Rattus* spp. A frequently used method is to make suitable substrates available by laying patches of materials such as flour, sand, talc or chalk in places where rodents are considered likely to be active. Shepherd and Greaves (1984) recommend applying a suspension of lampblack, in a volatile carrier, on to vinyl plates of consistent dimensions. Once the carrier has evaporated a thin coating is formed in which readily discernible footprints will be left by passing rodents. These plates can be scored simply as either marked or unmarked. For high-density populations, it may be necessary to adopt a scoring system based on the number of discernible tracks or the proportion of the plate that is marked. Because of variation in rodent activity with factors such as the weather, track plate scores need to be recorded for 3 or more separate days in order to obtain a single index of activity.

One possible source of bias in the tracking plate method is that the behaviour of individuals can change during the course of treatments. For instance, surviving animals may expand their home ranges, making it more likely that they will mark tracking plates, and so efficacy will be underestimated. Alternatively, the more wide-ranging individuals may be the most likely to succumb to the treatment, leaving behind animals with more conservative patterns of space use who are thus less likely to mark tracking plates. This would result in overestimates of efficacy. These potential sources of error can be minimized by ensuring that adequate numbers of plates are laid. Tracking plates are typically distributed in association with bait points or bait stations during rodenticide evaluations. This potentially excludes from both pretreatment and post-treatment censuses any animals whose home ranges do not include bait points or are actively avoiding baits, which would lead to an overestimation of efficacy. Instead, the distribution of plates should be independent of bait points and performed at a predetermined density. Using this approach, a calibrated tracking plate method has been developed for *Rattus norvegicus* on farms; this offers the estimation of absolute rat numbers (Quy *et al.*, 1993), although these authors found that tracking was the least reliable of the census methods that they evaluated for house mice.

FOOD AND WATER CONSUMPTION. Measuring changes in water consumption has been used with limited success for evaluating rodenticide treatments (Spaulding and Jackson, 1983). A more common method is to make unpoisoned food material available and to record consumption in a standard way both before and after treatment, so giving a measure of any change in rodent activity. Quy *et al.* (2009) found census baiting to be the most reliable and cost-effective of the methods they evaluated for house mice. However, a fundamental criticism of this approach is that the pretreatment census may represent a period of prebaiting, allowing the target animals to overcome their neophobic responses towards novel food placed in a novel context, a process that would not occur during a standard treatment. Hence, the resulting efficacy estimate might be inflated in comparison with a standard treatment. In order to minimize this potential prebaiting effect, the pretreatment census bait should be different from that used for the treatment, ideally in terms of appearance, taste, texture and location. There should also be a lag period between the end of census baiting and the beginning of the treatment, which should not be so long so that natural population processes (births, deaths and migration) are allowed to confound the effect of the treatment.

The EPPO guidelines for evaluating acute rodenticides against *Rattus* spp. recommend a pretreatment lag period of 14 days (EPPO, 1975). A post-treatment lag period is also recommended (7 days in the EPPO guidelines) to ensure that any animals affected by the treatment die before undertaking the post-treatment census. EU (2009) recommends pretreatment and post-treatment lag periods of between three and 14 days in commensal rats and mice. Both pretreatment and post-treatment census baiting periods must be of sufficient length for all animals to begin to feed freely if the two indices of activity are to be comparable. The EPPO guidelines suggest that 4 days is adequate but this is unlikely to be the case for all animals in all situations.

An alternative is to persist with census baiting until daily consumption has levelled off and take this asymptotic consumption as the census index.

For treatments involving the use of acute rodenticides, which contain an element of prebaiting in the recommended practical methodology, then prebaiting consumption can be used as a census index, thus avoiding the problem of confounding census baiting with prebaiting. There is, though, the possibility that some animals that survive such treatments will have done so through the development of a learned aversion to bait after consuming a sublethal dose. Consequently, a different material has to be used for the post-treatment census. It has been argued that if this material is chosen from a restricted range of cereals, then differences in palatability should not confound comparison between pretreatment and post-treatment censuses (Dubock and Rennison, 1977). The degree to which learnt aversions are expressed across this range of materials is, however, unknown, nor does this approach correct for enhanced neophobia to all novel foods arising from an association of aversive symptoms with exposure to a particular novel food (Robbins, 1981). These changes in behaviour would lead to overestimates of efficacy. Such learned behaviours are more likely to be associated with acute rather than chronic poisons. Nevertheless, the maximum interval between the conditional stimulus (in practice, the exposure to the poison bait) and the unconditional stimulus (in practice, the onset of symptoms) for a conditioned aversion to develop is unknown for rodents (Robbins, 1981). Hence, a degree of physiological resistance to a second-generation anticoagulant might still offer an individual a greater opportunity of learning to associate symptoms of illness with the bait before consuming a lethal dose, and thereby confound measures of efficacy. Nonetheless, no conditioned taste aversion has ever been demonstrated towards any anticoagulant rodenticide, although a transitory symptom-dependent aversion was reported by Smith *et al.* (1994). A further constraint on the choice of census bait is that it should not elicit hoarding behaviour, which may cause the overestimation of efficacy (Peardon, 1977).

The use of bait markers can provide useful insights into the outcome of rodenticide treatments and the factors contributing to their efficacy (Purdey *et al.*, 2003). This technique can be used to estimate both population size and the amounts of bait eaten per individual (Cowan *et al.*, 1987), the latter being important in understanding whether or not efficacy is being constrained by physiological resistance to the rodenticide (Quy *et al.*, 1995).

'SAMPLING GRAPH' METHOD. An alternative to the use of census baits that nonetheless relies on monitoring bait consumption has been widely used for evaluating the efficacy of chronic rodenticides against *R. norvegicus*. This involves establishing a standard expectation of changes in bait consumption during the course of a treatment and then comparing subsequent treatments with this standard (Drummond and Rennison, 1973). This became known as the 'sampling graph' method, and it originated as a means of detecting warfarin resistance, which was subsequently recommended for the evaluation of second-generation anticoagulants (EPPO, 1982). During the trials used to establish this method, the number of bait points from which bait was taken, i.e. the number of bait takes, reached a maximum at the first visit, i.e. 2 days after bait was first laid. Bait takes then declined until feeding ceased after 2–3 weeks. Drummond and Rennison (1973) expressed the number of bait takes on each visit as a proportion of the number of takes on the first visit, and showed that this proportion declined in an inverse linear relationship to the number of visits plotted on a logarithmic scale. The resulting regression line, with its 95% confidence intervals, represents the standard sampling graph (see Fig. 8.1). Evaluating the outcome of treatments by measuring bait-take frequency rather than bait consumption is simple, labour efficient and apparently worked well for small infestations in which the majority of animals rapidly begin to consume bait. However, as Quy *et al.* (1992) pointed out, a small take, representing, say, a sublethal dose to a fully anticoagulant-susceptible individual, is given equal weight to a large take representing lethal doses to several susceptible animals or a large take by a resistant animal.

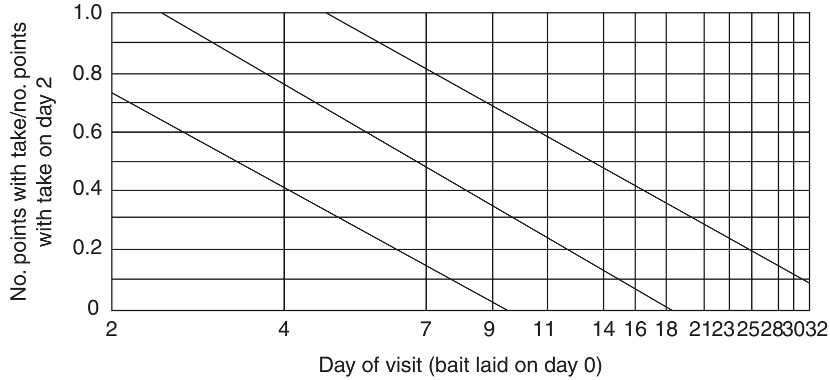

Fig. 8.1. The sampling graph, showing the regression line of decline in bait takes with treatment length and 95% confidence limits ($y = 1.41 - 1.11x$). The first visit is on day 2, i.e. 2 days after the bait was first laid. If for two successive visits during a treatment the proportion of points with takes lies above the upper limit, it is regarded as abnormally high (from Drummond and Rennison, 1973).

Drummond and Rennison (1973) demonstrated a good correlation between the number of bait points with takes and the absolute quantities of bait eaten, although this was based on data from only three farms, one of which involved takes from only eight bait points.

The most fundamental concern about the measurement of efficacy by monitoring bait consumption is that it only reflects changes in the size of the rodent population that is willing to consume such material. If some animals do not consume bait, during either the census or the treatment, then these animals will not be accounted for. Apparent treatment success may thus hide varying degrees of failure. In some circumstances, notably for field rodents and lagomorphs feeding predominantly on monocultures such as cereal or rice fields, bait might form a substantial proportion of the diet. It seems unreasonable, though, to expect that bait would always be adopted as the predominant component of the diet of opportunistic species, such as commensal rodents, living in heterogeneous habitats that offer a diversity of alternative food. Ecological variation, particularly in relation to the availability and predictability of such alternative food, may well lead to a higher proportion of animals consuming bait in some populations than others (Quy *et al.*, 1994). In these circumstances, a reliance on bait-based measures of efficacy would obscure an important component of the variation between populations in the outcome of rodenticide treatments. Only by using efficacy measures that are truly independent of bait consumption is it possible to disentangle the various behavioural and physiological factors that can influence rodenticide performance in the field (Cowan *et al.*, 1995).

Baiting methods for assessing efficacy may also be unreliable because of variation within populations. For instance, the behaviour of animals that succumb to the treatment may differ from that of those that survive. Some individuals may be less willing to consume baits, in other words novel foods, than others, i.e. they are more neophobic (Inglis *et al.*, 1996; see also Chapter 1). Such variation might be genetic in origin, for which there is little evidence in wild species, but which is the basis of the concept of behavioural resistance to rodenticide treatments (Berdoy and Macdonald, 1991; Brunton *et al.*, 1993), or might arise through prior experience. Whatever its origin, such variation is likely to leave a higher proportion of relatively neophobic animals in the post-treatment population (e.g. Brunton and Macdonald 1996), which are also less likely to consume census baits, so this process would lead to overestimates of efficacy.

Measuring bait consumption remains the most commonly used census method in field trials as it is recommended by both the EU (2009) and the EPA (Jacobs, 2011) regulatory guidelines, even though the approach can be compromised by a range of potential inherent biases and confounding factors, as described here. Hence, its use should always be augmented by at least one bait-independent method.

Quantifying Efficacy

The appropriate approach to quantifying efficacy is partly determined by the unit of measurement. For longitudinal evaluation, the survival of each animal observed represents a single observation. These observations are amenable to analyses based on the binomial distribution to estimate average survival rates for the populations to which they belong (e.g. White and Garrott, 1990). Of particular interest in studies of efficacy is comparison of the survival rates of animals exposed to different treatments. For this purpose, epidemiological methods are appropriate (e.g. Lee, 1980). Such techniques allow the pooling of data from individuals belonging to different populations, but exposed to the same treatment, in order to make comparisons with the survival of individuals from populations exposed to an alternative treatment, or, in a controlled experimental design, no treatment. Individuals whose fate is unknown, for instance through transmitter failure or undetected emigration, should be excluded from such analyses at the time of this disappearance (e.g. White and Burnham, 1999).

For data obtained by census methods, each population represents the unit of observation. Natural populations are rarely discrete or closed, i.e. subject to no emigration and immigration. For commensal rodents in temperate agricultural habitats, a discrete group of farm buildings often represents a useful means of defining an experimental unit, but even here, surrounding fields and hedgerows often contain reservoir populations that may influence the observed efficacy through reinvasion (Quy *et al.*, 1992). The concept of maintaining a 'buffer zone' surrounding the experimental area can be useful (Myllymäki, 1970). Here, data on population changes are only assessed for a central core of the treated area, the size of the surrounding buffer zone being commensurate with the known ranging behaviour of the target species. This is particularly important in field trials conducted in open-field agriculture, such as rice, oil palm and sugarcane (see Fig. 8.2), where treated plots are set out in a landscape which is more or less uniformly infested with rodents (e.g. Buckle *et al.*, 1984).

Having defined the study population, then efficacy can be measured in terms of the percentage change in population size (see Eqn 8.2 at the bottom of the page).

In controlled experimental designs, where populations are matched for relevant ecological variables and one acts as a control for natural changes in population size while the other is exposed to the treatment, a variant of Eqn 8.2 can be used (Henderson and Tilton, 1955):

$$100 \times \left\{1 - \left[\frac{(T_2 \times C_1)}{(T_1 \times C_2)}\right]\right\} \tag{8.3}$$

where T_1 and C_1 are the pretreatment census for treated and control populations, and T_2 and C_2 are the post-treatment census for treated and control populations, respectively.

The EC, EPA and EPPO guidelines for field evaluation all recommend two independent measures of efficacy to be made, one of which may be the use of census baits. For this approach to be meaningful, however, there must be a specified level of agreement between the measures. This agreement should be in absolute rather than relative terms. It is inadequate merely to demonstrate a significant correlation between measures as this may simply reflect one measure consistently underestimating efficacy relative to the other. One approach would be to demonstrate a lack of deviation from a slope of unity for the linear relationship between the two measures. Alternatively, a lack

$$100 \times \frac{(\text{pretreatment census} - \text{post-treatment census})}{\text{pretreatment census}} \tag{8.2}$$

Fig. 8.2. Field trials conducted in agricultural landscapes, such as these sugarcane fields, require rigorous experimental design. Treated buffer zones must be established around assessment areas to prevent rodents not exposed to the treatment under evaluation being counted in efficacy assessments. Plots receiving different experimental treatments must be separated by distances great enough to ensure that rodents are exposed only to the treatment being assessed and not to those applied in neighbouring plots. Roads and irrigation channels may be used to delineate plots, but these do not prevent rodent movements.

of a significant difference between the means of the measures in a paired test over a number of trials should be demonstrated. For evaluations of a single rodenticide formulation, the EPPO guidelines recommend that six to ten separate treatments should be carried out (EPPO, 1982). Particularly high- or low-density populations should be avoided, as should unusual or exceptional situations. For comparison between two treatments, at least six replicates should be performed for each. The design can then be either matched, in terms of identifying sites with similar ecological conditions, or unmatched, where the two treatments are randomly allocated to the available sites.

In experimental designs that seek to compare different treatments or the same treatment in different circumstances, for instance under different ecological conditions, then analysis of variance can be used to compare the means of the appropriate efficacy estimates. Variation in initial census size should be taken into account when using census baiting as a method of evaluating efficacy for commensal rodents (EPPO, 1975; Dubock and Rennison, 1977). This can be achieved by comparing final census values after their dependency on initial census values has been removed as a covariate. An alternative has been proposed by Huson (1980), which expresses the final census as a percentage of the initial census and uses this as the response variable in an analysis of variance. He showed by simulation that this appeared to be both a more accurate and a simpler solution to the problem than did the covariance approach.

The sampling graph method represents a special case as it does not provide an estimate of absolute efficacy for each individual treatment and so is not amenable to analyses of variance or covariance. Instead, if during a treatment there are two or more successive visits when the proportion of takes exceeds the upper 95% confidence limit, then the treatment is considered to be significantly less effective than the standard treatment used to generate the graph (Drummond and Rennison, 1973).

The historical perspective of the sampling graph method was as a means of detecting physiological resistance to warfarin, and this led to poor efficacy being interpreted as evidence of physiological resistance when applied to second-generation anticoagulants (e.g. Greaves *et al.*, 1982). However, a subsequent re-evaluation of data comparing the effectiveness of second-generation anticoagulants on *R. norvegicus* in Hampshire, UK, where resistance to difenacoum was known to be present, and in Powys, Wales, UK, where resistance to warfarin was widespread, showed that this interpretation was not always correct (Quy *et al.*, 1992). First, although maximum bait takes were, in general, recorded on the first visit during the Powys treatments, as suggested by the original sampling graph method, this was not the case in Hampshire. By taking the visit when the maximum number of takes was recorded as the starting point, irrespective of whether this was the first visit or not, some of the apparent differences in efficacy between Powys and Hampshire were accounted for. Quy *et al.* (1992) also pointed out that expressing takes as a proportion of maximum number of takes does not necessarily account for all variation due to infestation size. They therefore suggested an alternative analysis that includes the number of baits laid as a covariate to control for differences in infestation size. Furthermore, patterns of census bait consumption suggested that variation in behaviour between the Hampshire and Powys rats may have contributed to the observed differences in efficacy. This reanalysis illustrates that the sampling graph method is only a means of recognizing unexpectedly poor treatment outcomes without offering any insight into the variety of factors that determine efficacy.

Differences in behaviour that reflect ecological conditions are now known to play a key role in determining the outcome of rodenticide treatments that might previously have been ascribed to physiological resistance (Cowan and Quy, 2003). Other methods are therefore required to determine the role of physiological resistance, such as bait markers (Quy *et al.*, 1995) alongside the use of resistance detection tests (Prescott *et al.*, 2007), augmented more recently by DNA-based techniques (Buckle, 2013; see also Chapter 9).

Defining Efficacy Standards

Once the efficacy of a particular formulation in a given set of field conditions has been evaluated, what determines the decision as to whether it is an appropriate population management tool? In other words, what is an acceptable level of efficacy? Experience suggests that 100% control is an unreasonable expectation for a series of field trials. The perfect rodent population management strategy has yet to be realized. At the other extreme, any degree of efficacy might lead to use, especially in the absence of more effective alternatives. As a compromise, for formulations aimed at commensal rodents, the EPA guidelines require that at least 70% absolute efficacy must be demonstrated by two independent techniques and that no more than one rodent should be caught for every ten snap traps set at the end of the treatments (e.g. Spaulding and Jackson, 1983). A higher standard of efficacy is required in the European Union, where, in field trials, a decrease of the target infestation equal to or greater than 90% is necessary to satisfy the efficacy requirements of the regulatory authorities (EU, 2009).

The long-term consequences for efficacy of using a given formulation need to be considered. We know that there is variation among individuals within many rodent populations in both behaviour (see Chapter 1) and susceptibility to rodenticides, particularly anticoagulants (see Chapter 9). These traits are at least partly heritable. Hence, rodenticide treatments that are not 100%

successful potentially impose selection pressure favouring traits that offer protection, i.e. resistance in the widest sense, against subsequent treatments (Cowan *et al.*, 1995). In the long term, efficacy will fall unless measures are taken to prevent this process.

Second-generation anticoagulants are more toxic than their precursors such as warfarin. Nonetheless, formulated concentrations have not been reduced commensurately. Consequently, fully susceptible animals need to consume less bait in order to be exposed to a lethal dose and animals resistant to warfarin can be eliminated. Then again, the increased toxicity of these rodenticides offers the potential to use formulations (Palmateer, 1981) or baiting strategies (Greaves *et al.*, 1988) that result in individuals being exposed, on average, to less toxicant, while still maintaining efficacy. The benefits to be reaped from such control policies include reduced financial costs of treatments and perhaps reduced risk to non-target wildlife (Buckle *et al.*, 2012). There is, however, an increased probability that the least susceptible animals in the target population might be able to survive such treatments, resulting in selection pressure favouring resistant traits. Initially, this could occur with only marginal reductions in efficacy that would be unrecognized among the other sources of variation (Cowan *et al.*, 1995). A possible counter-strategy might be always to use the most toxic formulation available in every circumstance. This would be inappropriate not least through the increased risk to non-target species. Alternatively, given a sound understanding of the biology that influences efficacy, we could identify the most appropriate formulation for a given circumstance. A balance needs to be maintained between the absolute toxicity of the formulation to the least susceptible members of the target population and its acceptance under the relevant field conditions.

It is also important to recognize that the method of bait presentation can have a profound influence on outcome and needs to be tailored to the natural foraging behaviour of the target species (Quy *et al.*, 2003; Buckle and Prescott, 2011). Bait palatability as measured in captive animals is a poor predictor of efficacy of anticoagulants used against Norway rats in the field (Quy *et al.*, 1996). Nevertheless, the EPA guidelines suggest that particulate bait formulations containing slow-acting active ingredients, such as anticoagulants, must form 33% of the diet of laboratory animals offered a choice against a standard diet and achieve 90% mortality (Palmateer, 1981; Jacobs, 2011). Less stringent requirements are imposed by the EPA for wax-block formulations (25% palatability and 80% mortality). In the EU, laboratory animals must either consume at least 20% of their daily diet as the test formulation in choice tests or, if this level of consumption is not reached, mortality must be shown in the test to have been greater than 90%. Although adhering to these standards may have restricted the incidence of resistance, it has clearly not prevented its occurrence (Quy *et al.*, 1995). Therefore, there should be no relaxation of the bait acceptance standards even if efficacy can apparently be maintained with the use of more toxic materials in less palatable formulations. Complacency could accelerate selection for resistance, with the consequent impairment of currently the most effective rodent population management tools (Quy *et al.*, 1998).

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9 Resistance to Anticoagulant Rodenticides

H.-J. Pelz[1] and C.V. Prescott[2]
[1]*Vertebrate Research Group, Julius Kühn-Institut – Federal Research Centre for Cultivated Plants, Münster, Germany;* [2]*School of Biological Sciences, University of Reading, Reading, UK*

Introduction

The development and introduction of coumarin derivatives as rodenticides from the late 1940s onwards resulted in significant changes in rodent control. Due to their favourable properties – high susceptibility of rodents, particularly with Norway rats, their delayed action overcoming bait shyness, and the availability of vitamin K_1 as a complete antidote – anticoagulants soon became popular rodent-control agents and gradually replaced the old acute poisons. Today, in some regions of the world, they are the only registered active ingredients for effective rodent control of specific species. At the same time, the spread of resistance to many of the anticoagulant active ingredients is a matter of concern.

Definition of Resistance

The following definition of resistance was developed by Greaves (1994) for the first edition of this book. It defines resistance within criteria involving practical implications, the appropriate use of anticoagulants and genetic considerations:

> Anticoagulant resistance is a major loss of efficacy in practical conditions where the anticoagulant has been applied correctly, the loss of efficacy being due to the presence of a strain of rodent with a heritable and commensurately reduced sensitivity to the anticoagulant.

However, there is a wide range of variation in natural susceptibility to anticoagulant compounds in rodent species, which may be related to the specific habitat where the species evolved. Black rats (*Rattus rattus*) and house mice (*Mus musculus/domesticus*) are considerably less susceptible to anticoagulants than Norway rats (*Rattus norvegicus*). Relatively insensitive to some or all anticoagulants are some species that are resident in arid areas, like the Egyptian spiny mouse (*Acomys cahirinus*), Shaw's gerbil (*Meriones shawi*) and the golden hamster (*Mesocricetus auratus*) (Gill, 1992). Such variation in susceptibility, as well as slight sex-specific differences, are of great value to scientists investigating the mechanism(s) of resistance, but they do not fall within the definition of resistance given above.

History

Rodent resistance to warfarin and other 'first-generation' anticoagulants has now been known for more than 50 years, with the first population of warfarin-resistant Norway rats (*R. norvegicus*) being discovered in Scotland in 1958 (Boyle, 1960). Today, resistance against these anticoagulants in the three major commensal species (*R. norvegicus*, *R. rattus* and *M. musculus*) is common across continents (Table 9.1).

Genetics of Resistance

Norway rat (*Rattus norvegicus*)

Early genetic studies based on breeding experiments determined a dominant autosomal warfarin-resistance gene, denoted *Rw*, on chromosome 1 in Norway rats (Greaves and Ayres, 1967); and subsequent studies indicated the influence of modifiers on the expression of the gene (Greaves and Ayres, 1976). According to their origin and resistance properties, several geographically distinct resistant strains of Norway rats were described in the UK and the USA (Greaves and Ayres, 1982). These resistance types were originally designated Scottish-, Welsh-, Hampshire-, Berkshire- (UK) and Chicago- (USA) type resistance, thus identifying different resistance alleles in geographically distinct Norway rat populations. This was later confirmed by the detection of the gene for the vitamin K epoxide reductase complex subunit 1 (*VKORC1*) (Rost *et al.*, 2004), a gene that encodes an anticoagulant-sensitive component of the enzyme vitamin K 2,3-epoxide reductase (VKOR), which is known to be the target of the anticoagulants. Missense mutations leading to amino acid substitutions were found in this gene in warfarin-resistant rats (*Rw*-rats) as well as in warfarin-resistant mice (*War*-mice, see below) and in warfarin-resistant human (*WR*-human) patients. A number of region-specific mutations developed independently in this gene, each conferring a certain level of resistance to anticoagulants (Pelz *et al.*, 2005).

The geographically distinct resistant strains mentioned above are each characterized by a specific *VKORC1* mutation (Fig. 9.1), which results in a particular amino acid at a certain position being changed to a different amino acid: Leu128Gln in the Scottish-, Tyr139Ser in the Welsh- and Arg35Pro in the Chicago-type of resistance; the Hampshire- and Berkshire-type resistances both share the mutation

Table 9.1. Documented occurrence of anticoagulant resistance in commensal rats (*Rattus norvegicus* and *Rattus rattus*) and house mice (*Mus musculus*) based on laboratory resistance testing. (After Pelz *et al.*, 2005, revised.)

Country	*R. norvegicus*	*R. rattus*	*M. musculus*	References[a]
Australia		+		Saunders (1978)[a]
Belgium	+		+	Lund (1984)[a]; Baert (2003)[a]
Brazil	+			Neto (1986)
Canada	+		+	Siddiqi and Blaine (1982)[a]
Denmark	+	+	+	Myllymäki (1995)[a]; Lodal (2001)
Finland			+	Myllymäki (1995)
France	+	+	+	Myllymäki (1995)
Germany	+	+	+	Myllymäki (1995)
Great Britain	+	+	+	Myllymäki (1995); Kerins *et al.* (2001)[a]
Italy	+			Alessandroni *et al.* (1980)[a]
Japan		+		Naganuma *et al.* (1981)[a]
Malaysia		+		Lam *et al.* (1982)
Netherlands	+		+	De Jonge (1994)[a]
Sweden			+	Lund (1984)
Switzerland			+	Muhr (1981)[a]
USA	+	+	+	Jackson and Ashton (1986)[a]

[a]References cited by Pelz *et al.* (2005).

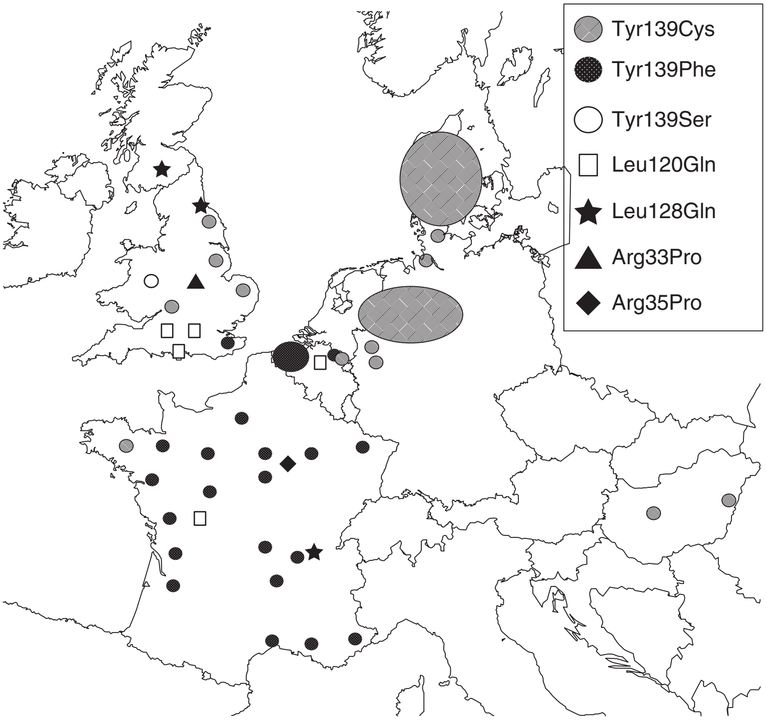

Fig. 9.1. Verified occurrence of sequence variants of the gene for the vitamin K epoxide reductase complex subunit 1 (*VKORC1*) mediating resistance to anticoagulant rodenticides (at least to warfarin) in Norway rat populations in Europe. Last update January 2012.

Leu120Gln. Other important and widespread *VKORC1* mutations in rats are: Tyr139Cys, which is common in Denmark and north-west Germany, but is also widely distributed in other countries (Rost *et al.*, 2009; Baert *et al.*, 2011; Buckle, 2013); and Tyr139Phe, which is common in France (Grandemange *et al.*, 2009), Belgium (Baert *et al.*, 2012) and the Netherlands (van der Lee *et al.*, 2011), and has also been found in South Korea and, recently, in Kent in the UK (Prescott *et al.*, 2011). The sensitivity of all these resistance strains to the different first- and second-generation anticoagulants has been discussed by Buckle (2013). Grandemange *et al.* (2009) studied resistance properties in a congenic Norway rat strain carrying the Tyr139Phe mutation introduced on to an anticoagulant-susceptible Sprague Dawley strain of Norway rat. Their results confirm the strong resistance-mediating characteristics of the homozygous *VKORC1* mutation to first-generation anticoagulants, and to bromadiolone and low doses of difenacoum (second-generation anticoagulants); there is a weaker effect in heterozygous individuals. More *VKORC1* sequence variants in rats have been identified, but their phenotypic effects are yet to be verified (Rost *et al.*, 2009).

House mouse (*Mus musculus/domesticus*)

A dominant autosomal warfarin-resistance gene orthologous to *Rw*, and denoted *War*, was determined on chromosome 7 in house mice (Wallace and MacSwiney, 1976). Three resistance-conferring *VKORC1* sequence variants have been found to be widespread in house mouse populations: Leu128Ser, Tyr139Cys and a linked group of sequence changes – Arg12Trp/Ala26Ser/Ala48Thr/Arg61Leu (Pelz *et al.*, 2011, see Fig. 9.2).

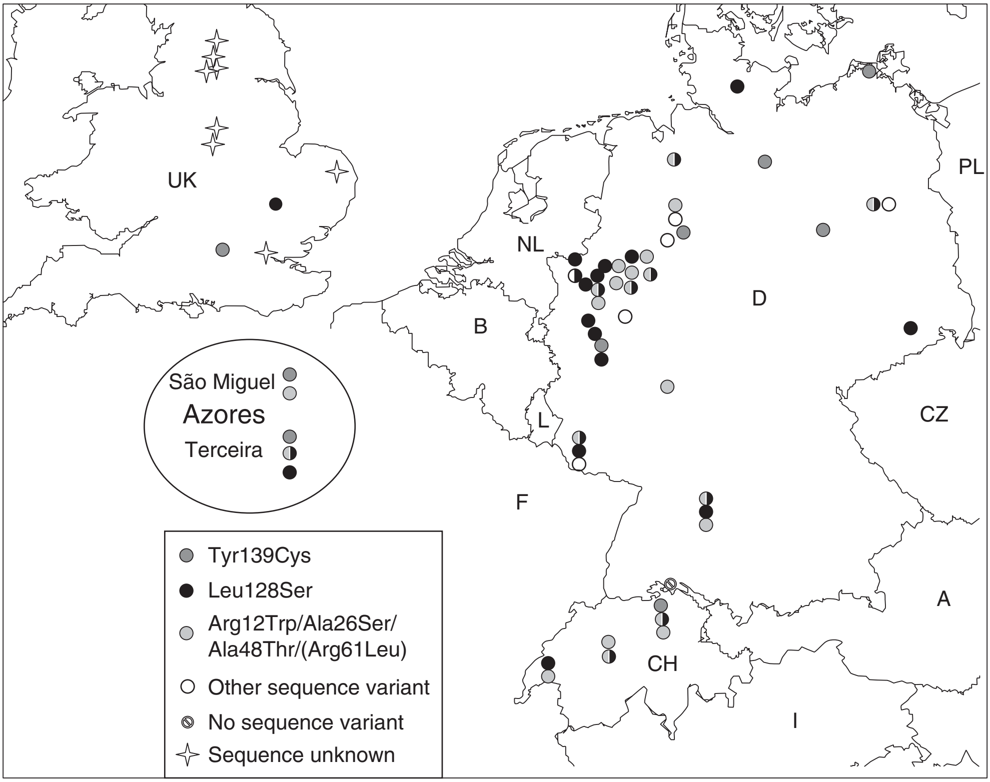

Fig. 9.2. Verified occurrence of sequence variants of the gene for the vitamin K epoxide reductase complex subunit 1 (*VKORC1*) mediating resistance to anticoagulant rodenticides in house mouse populations sampled in Germany, Switzerland and in the Azores (data from Pelz *et al.*, 2011). Shared dots indicate sites where combinations of sequence variants were found in individuals. In the UK, the origin of two wild-derived resistant house mouse breeding colonies with known sequence variants is indicated by the solid circles, and asterisks show locations where resistant house mouse populations have been detected in the past (see Rowe and Redfern, 1965; MacSwiney and Wallace, 1978).

Initial investigations of resistance in house mice have been aided by the maintenance of breeding colonies in the UK that are homozygous for the mutations Leu128Ser and Tyr139Cys.

The mutation Leu128Ser was originally derived from warfarin-resistant wild house mice that originated from the Cambridge area of the UK. In the 'Cambridge cream' strain (homozygous for Leu128Ser), the penetrance of the genotype was found to be affected by sex and modifier genes, which influenced the expression of the *War* gene (MacSwiney and Wallace, 1978). According to published research from the UK (mainly by F.P. Rowe and co-workers) with this strain, Leu128Ser (homozygous) mice are resistant to warfarin, and presumably other first-generation anticoagulants, but with incomplete penetrance in male animals. Some individuals also survived choice and no-choice trials with bromadiolone and difenacoum. It seems then that this mutation enables some of the mice to stabilize their vitamin K metabolism even when consuming anticoagulants of high potency over prolonged periods.

In the 'Reading' strain (homozygous for Tyr139Cys), the *War* gene appeared to be fully expressed in both males and females (Prescott, 1996). The strain was derived from wild house mice caught in the vicinity of

Reading, UK, and was found to be highly resistant to warfarin and bromadiolone (Prescott, 1996). Susceptibility to compounds of higher potency is currently largely unknown, though the strain is apparently susceptible to brodifacoum (C.V. Prescott, unpublished).

The third *VKORC1* sequence variant (Arg12Trp/Ala26Ser/Ala48Thr/Arg61Leu) is believed to have been transferred from *M. spretus* to *M. musculus/domesticus* by interspecific hybridization and then quickly spread over wide areas, presumably by freighting of individuals (Song *et al.*, 2011). Although the phenotypic effect is still to be verified, it is known to be associated with a substantial loss of rodenticide efficacy against first-generation anticoagulants (e.g. warfarin, coumatetralyl), as well as the second-generation compounds bromadiolone and, most probably, difenacoum.

Endepols (2010) studied the resistance-conferring effect of these complex sequence changes by means of laboratory tests. Compared with the wild type, susceptibility to coumatetralyl and bromadiolone was markedly reduced in the strain containing the sequence changes. Four of 20 individuals also survived a 5 day no-choice feeding test on difenacoum bait, suggesting that efficacy problems with this compound might also occur under practical conditions. Information on resistance to compounds of higher potency is currently unavailable.

Other rodent species

In breeding experiments with warfarin-resistant roof rats (*R. rattus*) in England, 25% of the offspring of resistant × resistant crosses, and 13% of the offspring of outcrosses, were resistant. In backcrosses to the susceptible strain, less than 1% of the offspring were resistant, indicating considerable instability in the trait. The results were taken to indicate a multifactorial basis for the resistance (Greaves *et al.*, 1976). In roof rats, there is now evidence of *VKORC1* sequence variants conferring resistance to anticoagulants. In a sample of roof rats (*R. rattus*, erroneously denoted as *R. norvegicus*) from Argentina, a Trp59Arg mutation was found, but in this case the resistance status of the population was unknown (Rost *et al.*, 2009; Díaz *et al.*, 2010). The same sequence variant characterized a roof rat population in a village close to Mölln, Germany, where 18 of 19 individuals carried the Trp59Arg mutation (89% homozygous). Reportedly, it was difficult to control this population using either bromadiolone or difenacoum, though poor bait consumption was a confounding problem.

Warfarin-resistant *R. losea* in southern China possessed an Arg58Gly *VKORC1* mutation, which was absent in susceptible individuals (Wang *et al.*, 2008). Elsewhere in China, one out of four warfarin-resistant *R. flavipectus* possessed a homozygous Tyr139Cys *VKORC1* mutation, and among 32 susceptible rats that did not survive the resistance test, one individual carried a heterozygous Tyr139Cys mutation (Huang *et al.*, 2011).

Some contradictory results suggest the existence of alternative ways of acquiring resistance, thus emphasizing the need for further research. First, Heiberg (2009) identified low-level resistance in a sample of Danish sewer rats (*R. norvegicus*) using blood clotting response (BCR) tests, but none of 11 resistant individuals carried *VKORC1* sequence changes that would cause amino acid substitutions. These findings need further corroboration. The second case concerns a warfarin-resistant rat strain originating from the Welshpool area of the UK; this was first established in 1967 at the University of Wisconsin, and later maintained at Wake Forest University School of Medicine in North Carolina, USA. It is known that this rat strain showed the Welsh-type resistance characteristics (Hermodson *et al.*, 1969). Samples of this strain kept in the UK, and wild resistant rats trapped later from the same locality, all carried the Tyr139Ser mutation (Pelz *et al.*, 2005; Rost *et al.*, 2009). However, Wajih *et al.* (2004), working with the descendants of the American breeding colony, did not find *VKORC1*-sequence variants in these animals despite classifying them as ‘resistant’ using the BCR resistance testing methodology. Surprisingly, they were also unable to verify differences in VKOR activity between susceptible and resistant animals, in contrast to previous studies with this strain (e.g. Zimmermann and Matschiner, 1974; Hildebrandt and Suttie, 1982).

Pleiotropic effects of the resistance trait

A number of usually disadvantageous effects are known to accompany anticoagulant resistance. It is most likely that such 'costs' are induced by structural changes in the proteins caused by the resistance-conferring mutations.

Some of the *VKORC1* sequence variants result in an increased dietary requirement for vitamin K, in particular in the Welsh resistant rat strain (Tyr139Ser), in which the vitamin K requirements of heterozygotes and homozygotes are, respectively, about two to three and 20 times greater than those of susceptible rats (Hermodson *et al.*, 1969). Rats of a homozygous resistant strain from Hampshire (Leu120Gln) were reported to require even larger amounts of vitamin K to restore normal blood clotting activity than the Welsh resistant strain (Greaves and Cullen-Ayres, 1988).

Research at the University of Reading observed the effect of feeding vitamin K-deficient diets on blood clotting activity in different UK resistant strains of Norway rat. This work showed that vitamin K deficiency caused a greater prolongation of clotting time in the Welsh strain (Tyr139Ser) than in the Hampshire strain (Leu120Gln), with a greater effect in males than females in homozygous animals of both strains. The extent of the effect was dependent on the source of the vitamin K-deficient diet. Purchased diets were less effective in inducing vitamin K deficiency than diets manufactured in the laboratory. Using this technique, it was not possible to detect a prolongation of clotting time in heterozygous animals fed a vitamin K-deficient diet, and this difference has since been used in the laboratory to genotype resistant animals. Further studies have revealed that Berkshire (Leu120Gln) homozygous resistant rats also develop a prolonged clotting time when fed a vitamin K-deficient diet. In contrast, the Leu128Gln (Scottish), Tyr139Phe and Tyr139Cys variants have only a moderately increased requirement for vitamin K in the homozygous condition (Martin, 1973; Markussen *et al.*, 2003; Jacob *et al.*, 2012). The homozygous strain of 'Reading' resistant house mice (Tyr139Cys) also developed a prolonged clotting time when maintained on a vitamin K-deficient diet, although the magnitude was less than that seen in the Welsh (Tyr139Ser), Hampshire (Leu120Gln) and Berkshire (Leu120Gln) strains of resistant Norway rats. In summary, it can be stated that homozygous Welsh, Hampshire and Berkshire rats, and homozygous Reading mice, go vitamin K deficient in the laboratory following an extended no-choice feed on a vitamin K-deficient diet. However, it is more difficult to get mice to go vitamin K deficient than it is to achieve this in the three strains of resistant rats. Differences in the vitamin K-deficient diets used in laboratory testing may account for contrasting results between laboratories.

For the strains that go vitamin K deficient, there is relatively strong natural selection against resistant homozygotes in the absence of anticoagulants. Studies using the Tyr139Ser Norway rat strain show a markedly decreasing incidence of resistance over periods of 2–4 years when no anticoagulants were used. With a Norway rat infestation on a Welsh farm, Partridge (1979) observed a decline in the incidence of resistance from 80 to 33% over an 18 month period. The relative fitness of the resistant homozygote, heterozygote and susceptible homozygote, in the absence of anticoagulant selection, were estimated to be respectively 0.46, 0.77 and 1.00, suggesting that resistance might largely disappear from untreated populations in 15–25 generations. With intermittent application of a resisted anticoagulant, there would be the potential for 'heterozygous advantage', with heterozygous animals having greater fitness than homozygous resistant animals in the absence of the anticoagulant, and having an advantage over susceptible animals during the actual rodenticide treatment.

In contrast, breeding studies with the bromadiolone-resistant Tyr139Cys strain of Norway rat in Denmark (Heiberg *et al.*, 2006) did not result in selection against the resistance genotype. The proportion of resistant individuals in the absence of anticoagulant selection remained mostly unchanged over the 2-year study of breeding rat colonies in indoor pens, although the resistance trait did seem to interfere with breeding success. Jacob *et al.* (2012) found slight effects on reproduction in a breeding study with the Tyr139Cys strain of Norway rat in Germany. In contrast, reduced overall reproductive success was found among Tyr139Ser (Welsh) and Leu120Gln (Hampshire) Norway rat breeding colonies, but not among those of Leu128Gln (Scottish) and Leu-120Gln (Berkshire) resistant rats (MacNicoll *et al.*, 2001).

Furthermore, in a Tyr139Cys colony derived from wild Norway rats in Germany, the mutation was found to promote arterial calcification (Kohn *et al.*, 2008). In homozygous males, the aorta of the heart was distinctly mineralized, and the renal arteries were also mineralized in homozygous and heterozygous rats, regardless of sex.

Mechanisms of Resistance

The vitamin K cycle

Nutritional needs for vitamin K are usually met by normal dietary intake. Vitamin K in its reduced form (vitamin K hydroquinone) is an essential cofactor for the carboxylation of glutamate residues to calcium-binding γ-carboxyglutamate residues (Gla). This post-translation step is required for the activation of precursor proteins in the production of the active blood clotting factors II, VII, IX and X. Similar vitamin K-dependent Gla-proteins are also known to play key roles in the regulation of a number of other proteins, including one involved with bone metabolism.

During the above carboxylation reaction, the vitamin K hydroquinone is oxidized to vitamin K 2,3-epoxide which is, in turn, reduced to the hydroquinone by the enzyme VKOR. This system is called the vitamin K cycle (see Chapter 6), and allows each vitamin K molecule to be recycled up to 10,000 times. Incomplete carboxylation, as caused by vitamin K deficiency, can lead to the impairment of blood coagulation and spontaneous haemorrhages.

Biochemical resistance

Researchers mostly agree that VKOR plays a key role as the target for anticoagulants. They inhibit the enzyme and thus block the activation of the vitamin K-dependent blood clotting factors. The biochemical mechanism of anticoagulant resistance has been studied in several geographic strains/*VKORC1* variants of the Norway rat. Amino acid substitutions in VKOR seem to alter its structure and function (Li *et al.*, 2010), resulting in decreased sensitivity to or reversibility of anticoagulant inhibition, depending on the strain characteristics. Recombinant expression of *VKORC1* constructs in HEK293 cells demonstrated that mutations at Tyr139 decrease sensitivity to warfarin to varying degrees, while mutations at other positions dramatically reduce VKOR activity (Pelz *et al.*, 2005; Rost *et al.*, 2009). Earlier studies described both decreased activity and decreased sensitivity to warfarin inhibition for the Welsh and Hampshire strains, and reversible inhibition by warfarin for the Scottish and Chicago strains, in contrast to the prolonged inhibition found in the susceptible strain (Misenheimer and Suttie, 1990; Thijssen, 1995). Warfarin- and bromadiolone-resistant Danish house mice were found to show similarities to the Welsh-type resistance of rats in the sensitivity of VKOR (Misenheimer *et al.*, 1994).

It was hypothesized that these mutations, in addition to generating structural changes in the protein generated from the *VKORC1* gene, may also induce compensatory mechanisms to maintain blood clotting. Indeed, variations in metabolism and clearance are known to influence the efficacy of anticoagulants (Misenheimer and Suttie, 1990; Markussen *et al.*, 2008).

Distribution and Occurrence of Resistance

Norway rat (*Rattus norvegicus*)

VKORC1 sequencing is now being deployed widely across Europe to identify both the extent and incidence of the various *VKORC1* mutations, and is seen as a significant improvement on conventional laboratory resistance tests, both in terms of efficiency and cost. Figure 9.1 depicts the documented occurrence of *VKORC1* sequence variants in continental Europe and the British Isles. Among the variants with confirmed impact on the resistance status, mutations at position 139 of the gene are prevailing. Overall, the most widespread variants are:

- **Tyr139Cys**: prevalent in Denmark and Germany; found in parts of France (Brittany), Hungary, the Netherlands and the UK (at least four localities).
- **Tyr139Phe:** prevalent in France and Belgium and also found in the Netherlands, in Kent (UK) and, outside Europe, in South Korea.
- **Tyr139Ser**: conferring 'Welsh-type resistance', known only from the Anglo–Welsh border area centred at the town of Welshpool.
- **Leu120Gln**: known in the UK from Hampshire and Berkshire, and now more widely spread across central southern England; also found in some parts of France and in Belgium.
- **Leu128Gln**: the mutation conferring 'Scottish-type resistance' is found in Scotland, northern England and in a few locations in central France.
- **Arg35Pro**: the mutation conferring Chicago-type resistance, found in rats from the Chicago/USA area and in Europe in one location in central France only.
- **Arg33Pro**: found in rats from Nottinghamshire, UK.

The results of laboratory and field studies indicate that most of the genetic resistance variants confer practical resistance to first-generation anticoagulants. Mutations at *VKORC1* position 120 and 139 also impair the efficacy of bromadiolone and difenacoum (except for Tyr139Ser). In *R. norvegicus*, there is currently no evidence that the highly potent compounds of brodifacoum, difethialone or flocoumafen may be affected. The effects of the most common *VKORC1* sequence variants are depicted in Table 9.2. The effectiveness of the first- and second-generation anticoagulants against many of these Norway rat genetic resistance variants has been discussed by Buckle (2013).

Table 9.2. Effects of sequence variants of the gene for the vitamin K epoxide reductase complex subunit 1 (*VKORC1*) on the efficacy of anticoagulant compounds in rat (*Rattus norvegicus*) control.

VKORC1 sequence variant	Effect on control measures
Arg33Pro	Known from laboratory experiments to confer resistance to warfarin
Arg35Pro	Known from laboratory and control experiments to confer resistance to warfarin
Leu120Gln	Strong resistance to first-generation anticoagulants; second-generation anticoagulants bromadiolone and difenacoum mostly ineffective; bromadiolone more effective than difenacoum
Leu128Gln	Strong resistance to warfarin and diphacinone; coumatetralyl mostly ineffective
Tyr139Cys	Strong resistance to first-generation anticoagulants; bromadiolone and difenacoum mostly ineffective where the incidence of resistance in rat populations is high; difenacoum more effective than bromadiolone
Tyr139Phe	Laboratory experiments revealed resistance to first-generation anticoagulants and to bromadiolone; difenacoum may also be impaired
Tyr139Ser	Strong resistance to warfarin, coumatetralyl mostly ineffective; second-generation anticoagulants effective, despite a low resistance factor to bromadiolone

In wild populations of Norway rats, the incidence of resistance to first-generation anticoagulants in areas in which it is established has been reported commonly to be in the range 25–85% (Greaves, 1994), although in more recent studies, an incidence of 100% is not uncommon (Quy *et al.*, 1995; Prescott *et al.*, 2011). Experience suggests that the level of resistance is not evenly spread over an area but rather builds up in pockets, e.g. on specific farms in an area, depending on the selection pressure acting on the population from control measures (Lodal, 2001; Pelz, 2001). The average rate of spread of warfarin resistance in populations in rural areas of Britain is reportedly 5–8 km $year^{-1}$, which is consistent with the known mobility of the species. The spread is variable, however, and sometimes seems to be negligible over periods of 20 years or more. Accidental transportation of resistant rats may occur, but it is usually considered that widely separated foci of resistance have originated independently (Greaves, 1994).

House mouse (*Mus musculus/domesticus*)

Since 1961, difficulties in house mouse control using first-generation anticoagulants have been experienced widely in many countries (see Table 9.1). Resistance to bromadiolone and, to a lesser extent, to difenacoum also seems to be quite common (Rowe *et al.*, 1981; Myllymäki, 1995). Denmark and the UK have even reported a degree of resistance to brodifacoum in house mice (Myllymäki, 1995). The only study so far on the distribution of resistance-conferring *VKORC1* variants in house mice (Pelz *et al.*, 2011) suggests that Leu128Ser, Tyr139Cys and the linked group of sequence changes Arg12Trp/Ala26Ser/Ala48Thr/Arg61Leu (now known as the *spretus* group) are most common. Their occurrence in different parts of Germany, Switzerland and the UK, and in the Azores, indicates that they are widespread all over Europe in places where rodent control is routinely carried out.

Figure 9.2 depicts the distribution of resistant house mice across Europe, the British Isles and the Azores, according to samples taken to date. Samples from the Azores came from the islands of Terceira and São Miguel. All individuals from Terceira carried either the Tyr139Cys or the Leu128Ser mutation, while about half of the individuals from São Miguel carried the Tyr139Cys mutation. Recently, the *spretus* group was also detected in house mice from São Miguel (A. Esther, Julius Kühn-Institut, Germany, personal communication). It is hoped that ongoing studies on the effect of different *VKORC1* sequence variants and their combinations will improve our knowledge of anticoagulant resistance in house mice and its impact on field efficacy for the different active ingredients.

Other species

Resistance to first-generation anticoagulants has been reported several times for *R. rattus* (see Table 9.1). There is also evidence for this type of resistance in other species, including *R. tiomanicus*, *R. losea*, *Bandicota bengalensis* and *Holochilus sciureus*.

The Practical Effects of Resistance and Cross-resistance

Cross-resistance

The development of resistance in a population of rodents is not compound specific, but confers an effect on a range of anticoagulant active ingredients. When a strain of rodents that is resistant to one anticoagulant is also resistant to another to which it has not been exposed, it is said to show cross-resistance.

The degree of cross-resistance is ascertained by comparing the resistance ratios of the two compounds. Resistance ratios are a useful measure of the magnitude of the resistance, and are usually determined as the ratio between the ED_{50} values of the resistant and susceptible strains, where the effective dose (ED) has been estimated to achieve either mortality or a specified prolongation of clotting time in 50% of animals tested (see Prescott *et al.*, 2007). In practice, resistance ratios determined at higher mortality percentiles (e.g. ED_{90}) may be of greater relevance to practical control, but such determinations are excessively costly, and estimates extrapolated from data designed to be efficient at the LD_{50} level may be unreliable.

For reasons of cost and practicality, few attempts have been made to estimate resistance ratios, even at the LD_{50} level (Table 9.3), and the available data indicates that warfarin-resistant rodents possess similar levels of cross-resistance to other first-generation anticoagulants, lower cross-resistance to second-generation anticoagulants such as bromadiolone or difenacoum, and much lower, usually unimportant, cross-resistance to the second-generation anticoagulants brodifacoum, flocoumafen or difethialone.

Practical resistance versus technical resistance

For the first-generation anticoagulants, Norway rat resistance ratios greater than 2000 have been determined, but for second-generation anticoagulants, resistance ratios are generally much lower, typically less than seven (see Table 9.3). Clearly, a 2000-fold loss of anticoagulant toxicity is of much greater practical significance than a sevenfold loss.

Table 9.3. Resistance factors to anticoagulants at the LD_{50} level for laboratory strains of the Norway rat homozygous for warfarin-resistance genes and from three localities. (After Greaves and Cullen-Ayres, 1988.)

		Resistance ratios		
Anticoagulant	Sex	Welsh	Scottish	Hampshire
Warfarin	M	97.1	51.5	–
	F	2296.3	115.9	–
Coumatetralyl	M	33.7	34.0	–
	F	168.5	56.2	–
Difenacoum	M	1.3	3.4	3.9
	F	1.1	2.7	4.1
Bromadiolone	M	2.7	2.3	1.5
	F	6.9	2.5	2.9
Brodifacoum	M	1.0	2.5	2.0
	F	1.1	2.7	2.0

Thus, Drummond and Wilson (1968) showed that warfarin-resistant Norway rats could withstand doses of warfarin more than 100 times the largest dose survived by non-resistant rats; yet, contrastingly, Greaves *et al.* (1982) showed that putatively difenacoum-resistant rats succumbed to a dose of difenacoum only five times greater than the norm for susceptible rats.

The term 'practical resistance' has been proposed for cases where resistance ratios are sufficiently high that an acceptable level of control is unlikely to be achieved; and the term 'technical resistance' has been proposed for cases where the resistance is unlikely to have an effect on treatment outcome (Prescott *et al.*, 2007). For each active ingredient, 'practical resistance' will occur in a population of rodents where the resistance ratio is greater than a particular threshold; and the magnitude of this threshold will depend on the ED_{50} of the target susceptible strain and on the concentration of the active ingredient in the bait formulation applied.

Significance of low-grade resistance and cross-resistance

Resistance is inconsequential when the resistance ratio is low in relation to the field dosage rate of the anticoagulant. For example, the 70-fold decrease in susceptibility to coumatetralyl detected experimentally in the Norway rat in Britain in the 1960s failed, despite dire predictions, to cause control problems. This was apparently because the concentration of coumatetralyl in commercial baits was high enough to ensure toxicity to the resistant strain (Greaves and Ayres, 1969). Similarly, in another UK locality, a slight decrease in susceptibility to brodifacoum was detected by means of laboratory tests with bait containing 5 ppm brodifacoum (one tenth of field strength), with no evidence of a practical effect on treatment outcome (Gill *et al.*, 1992).

By contrast, in the same general locality, a fourfold resistance to difenacoum was associated with a widely recognized control problem, even though this degree of resistance was thought to be insufficient to account for the problem (Greaves and Cullen-Ayres, 1988). However, subsequent investigations indicated that the control difficulties were primarily due to poor bait consumption, probably resulting from the open storage of large quantities of cereals in the infested area. Similar control problems were encountered in a nearby ecologically similar area where there was no resistance, and control problems did not occur in an ecologically dissimilar area where there was a similar degree of resistance (Quy *et al.*, 1992a,b).

A minor loss of sensitivity to the anticoagulant is always liable to hamper control if bait avoidance behaviour, or some other baiting problem, prevents adequate consumption of the rodenticide bait, because such factors can cause control problems even when resistance is completely absent. To then equate a minor loss of sensitivity (which requires for its expression a special peculiarity of behaviour or environment) with full physiological resistance is to muddle the issue.

Detection tests for anticoagulant resistance

Resistance detection tests are important because obvious dangers can arise from a failure to detect resistance, and because a false diagnosis of resistance can lead to inappropriate countermeasures, wasted research efforts and neglect of the true factors responsible for control failures (EPPO, 1995).

Confirmation of field resistance

Resistance is usually first suspected when an anticoagulant fails to control an infestation in the field, contrary to established experience. Mere suspicion is, even if well informed, only a starting point. The loss of field efficacy needs to be documented and, preferably, quantified. To justify a provisional diagnosis of field resistance, investigations are required to exclude contributory causes of failure, such as defective formulation or application technique, lack of adequate bait uptake by the rodents, movement of new rodents into the treated area, misidentification of the rodent species or removal of bait by other species. A quick procedure, based purely on the visual observation of bait takes, has been described by Drummond and Rennison (1973) for *R. norvegicus*, and has proved to be of considerable practical utility (see Chapter 8). Nevertheless, the use of additional techniques is advisable to verify the treatment outcome, such as census of the rodent population before and after treatment (i.e. using tracking patches and/or consumption of a census bait), weighing of the anticoagulant bait to quantify persistent bait consumption, radio tagging to verify the fate of rodents exposed to the anticoagulant, and chemical tagging of the bait itself to verify bait consumption by the animals that survive the treatment.

Verification of anticoagulant resistance in the field usually requires sampling from the field population and subsequent studies in the laboratory; and a number of well-established laboratory methodologies are available for this.

The lethal feeding period (LFP) test

In the lethal feeding period test, as developed by the World Health Organization (WHO), a laboratory baseline is first established by feeding groups of susceptible rodents on the rodenticidal bait in a no-choice situation for various fixed periods of time, and subjecting the mortality results to probit analysis (WHO, 1982; EPPO, 1995). The LFP_{99} (i.e. the lethal feeding period equivalent to the LD_{99} – rounded up to the next whole day) is then used as a discriminating dose to detect resistance in the samples of rodents in which resistance is suspected. Published examples of LFP_{99} values derived by this method include, for the Norway rat, 6 days feeding on 50 ppm warfarin, 5 days feeding on 50 ppm difenacoum and 7 days feeding on 5 ppm brodifacoum (Drummond and Wilson, 1968; Redfern and Gill, 1978; Gill and MacNicoll, 1991). Survival of the discriminating dose is not proof of resistance, but signals the need for further investigations.

The LFP test can be robust and has other merits, but various problems may be encountered in its use. Estimates of the

LFP_{99} usually have high fiducial limits, because they are derived using minimal numbers of animals (for ethical reasons) and they are invariably estimated by extrapolation. In addition, uncontrolled variation in the dose of anticoagulant consumed by the susceptible animals can produce heterogeneity in the baseline data. When applying the test to potentially resistant wild-caught animals, many will be poor feeders (particularly when housed in a laboratory environment), thus introducing subjectivity in the final assessment of resistance.

For the second-generation anticoagulants, their high toxicity would be expected to achieve complete mortality of the susceptible strain following a 1 or 2 day no-choice feed (e.g. Buckle *et al.*, 1982), and would, therefore, preclude probit analysis of the resulting mortality data; and reducing the concentration of the anticoagulant formulation to get around this problem would substantially impair the face validity of the procedure.

The full WHO method is now rarely used, and many authors reporting its use actually feed the anticoagulant bait for an arbitrary period, such as 6 days for the Norway rat, 10 or 21 days for the house mouse, and 6 or 12 days for the roof rat. Though the validity of the shorter tests is often questionable, the use of an arbitrary feeding period as a resistance screening procedure has many advantages, and animals that show no signs of toxicity after feeding in the laboratory on bait containing the field concentration of the anticoagulant may certainly be considered to be resistant for many purposes.

Blood clotting response (BCR) tests

BCR tests developed to date are based on the measurement of blood clotting activity either 24 h or 96 h after administration of a specific dose of anticoagulant. The blood-clotting activity is measured using thromboplastin reagents that were developed for human warfarin therapy, and that detect limiting concentrations of the four vitamin K-dependent blood clotting factors (factors II, VII, IX and X). Test animals are determined to be either a 'responder' or a 'non-responder', depending upon the prolongation of their clotting time. Traditionally an animal is considered to be a responder if its plasma per cent coagulation activity (PCA) is less than a specified value, and coagulation times are converted to PCA using calibration curves based on serial dilutions of normal plasma in saline.

For warfarin (Martin *et al.*, 1979), chlorophacinone and diphacinone (Prescott and Buckle, 2000), blood clotting activity was measured 24 h after dosing, and a test animal was deemed to be a 'responder' if its clotting time was equivalent to a PCA of less than 17%. For difenacoum (Gill *et al.*, 1993) and bromadiolone (Gill *et al.*, 1994), blood clotting activity was measured 96 h after dosing, and a test animal was deemed to be a 'responder' if its clotting time was equivalent to a PCA of less than 10%.

The BCR tests for warfarin, chlorophacinone, diphacinone and bromadiolone were developed by determining the 'discriminating doses' that would make 99% of susceptible animals respond (i.e. the ED_{99} for warfarin, chlorophacinone and diphacinone, and the upper 95% fiducial limits of the ED_{99} for bromadiolone). Rodents that did not produce a BCR 'response' following administration of the 'discriminating dose' were classified as resistant. In contrast, the difenacoum BCR test was not based on the response of susceptible animals, but was developed to produce results that were comparable with those generated by the difenacoum LFP test. See EPPO (1995) for more details.

Prescott *et al.* (2007) raised important concerns about using PCA to differentiate 'responders' from 'non-responders' in BCR tests, and about using the ED_{99} response of susceptible animals to establish the 'discriminating dose' of the resistance test. Using two thromboplastin reagents with different sensitivities (with values on the International Sensitivity Index of 1.4 and 0.89, respectively) they found marked differences in the resulting PCA calibration curves. They concluded that PCA calibration curves are not appropriate for establishing the BCR 'discriminating dose', as there is poor calibration curve replication when determined using the same thromboplastin reagent, and marked differences in the calibration curves when determined using different thromboplastin reagents. These differences are particularly marked at low dilutions (i.e. at PCA values below 20%). As the published BCR tests for warfarin, chlorophacinone, difethialone, bromadiolone and difenacoum are based on PCA calibration curves and do not specify the thromboplastin reagent to be used, the tests are invalid and should not be used.

Resistance tests based on the response of susceptible animals rely on the statistical analysis of dose response data generated using minimal numbers of animals. Probit, logit and similar analyses are designed for the efficient estimation of the ED_{50}. For mathematical reasons, estimates are increasingly subject to error at higher percentiles, and estimates of the ED_{99} will vary considerably when determined using the different available statistical methodologies.

A standardized BCR resistance test was later developed for both Norway rats and house mice against the active ingredients bromadiolone, difenacoum, difethialone, flocoumafen and brodifacoum, and for Norway rats against the active ingredients warfarin, diphacinone, chorophacinone and coumatetralyl (Prescott *et al.*, 2007). The technique used for this determines blood clotting activity 24 h after administration of a specific dose of anticoagulant, and differentiates a 'responder' from a 'non-responder' using the international normalized ratio (INR).

In human haematology, differences in the sensitivity of different thromboplastin reagents are accommodated using a WHO standard. Each thromboplastin reagent is provided with an international sensitivity index (ISI) and a list of clotting times tabulated against the corresponding INR. The ISI is a measure of the sensitivity of the thromboplastin reagent, and the INR is the multiple of normal human clotting time that would have been obtained had the WHO reference thromboplastin reagent been used. In the standardized BCR resistance test, a rodent is considered a 'responder' if it has a clotting time equivalent to an INR equal to or greater than five.

For each active ingredient and species combination, dose response data are subjected to probit analysis to determine the dose required to achieve the ED_{50} response. A discriminating test dose of twice the ED_{50} can then be used for the initial identification of resistance, and will provide a more conservative assessment of resistance than previous published methods based on the ED_{99} response. Higher multiples of the ED_{50} can be used to assess resistance factors, in order to predict the likely impact of resistance on field control. For example, assuming the incidence of resistance is 100%, and following administration of a dose of six times the ED_{50}, if 50% of animals tested are found to be 'responders', this would indicate a resistance factor of approximately six at the ED_{50} level. Buckle *et al.* (2007) and Endepols *et al.* (2007) have used the BCR methodology in this way to assess resistance factors prior to conducting a fully monitored field trial, in an attempt to link resistance factors (for an active ingredient of known formulation strength) with treatment outcome.

Although the use of INR should take into account differences in the sensitivity of the different thromboplastin reagents that are commercially available, some laboratories have experienced difficulties in replicating the susceptibility data of Prescott *et al.* (2007; see above). These discrepancies require further investigation, but one option to overcome this problem may be to use the same thromboplastin reagent as in the original study (Diagen freeze dried rabbit brain thromboplastin reagent manufactured by Diagnostic Reagents Ltd, Thame, UK).

Molecular resistance tests

The identification of a basic anticoagulant resistance gene (Rost *et al.*, 2004) provided an opportunity for the development of a new resistance testing methodology based on molecular biological techniques. The occurrence of specific mutations in the *VKORC1* gene sequence correlates strongly with the results of BCR tests for resistance (Pelz *et al.*, 2005; Endepols *et al.*, 2012). The molecular genetic testing procedure can be performed using tissue samples of the target rodent population. Apart from sequencing the three exons of the *VKORC1* gene, specially designed DNA probes can be used to detect specific resistance-conferring mutations in the population under study. Only a few millimetres from the tip of a rodent tail are required as a viable tissue sample. As faeces usually contain a few intestinal cells, species-specific genetic information can also be gathered using droppings. The technique was first applied by Höss *et al.* (1992) and has subsequently proved effective in a number of investigations with different species (e.g. Reed *et al.*, 1997; Kohn *et al.*, 1999; Ernest *et al.*, 2000). Although rodent faecal pellets can be a useful resource for resistance diagnosis, the laboratory procedure is more prone to contamination, and the preparation of faecal pellets requires a special extraction procedure and an additional step for the accumulation of rodent DNA. In order to avoid repeated sampling of specific individuals stratified sampling of droppings across the sampling site is recommended.

Both tissue and faeces sampling can adequately reflect the occurrence of resistance-conferring mutations in a given population. To evaluate the magnitude of the resistance it is necessary to know the resistance factor of the sequence variant(s) detected. An assessment of the resistance factor should be conducted for each sequence variant and their combinations, against the anticoagulant compounds in question, to provide information about the likely impact of the mutation on field control. Once the resistance types resulting from specific *VKORC1* sequence variants have been characterized, adequate management strategies can be developed and applied.

Management of Resistance

What is resistance management?

The immediate aim of resistance management is to prevent or retard the development of resistance to a given anticoagulant, thus permitting its continued use. The ultimate aim is to reduce or eliminate the adverse consequences of resistance. This central concept can be achieved more efficiently and cost-effectively by integrated, cohesive and systematic action. In this sense, it has much in common with integrated pest management (IPM), and uses the same wide range of techniques. Resistance management should be distinguished from extemporary or makeshift actions that may be taken to control resistant infestations. Resistance management guidelines have been published by the Rodenticide Resistance Action Committee of CropLife International (RRAC, 2003), the Rodenticide Resistance Action Group of the UK (RRAG, 2010, 2012) and the German Fachausschuss Rodentizidresistenz (FARR, 2012).

Practical attempts at resistance management

A number of attempts to manage resistance in *R. norvegicus* in Britain are mentioned by Smith and Greaves (1987). The most important of these was an effort to exterminate individual resistant infestations, which was apparently successful in seven out of 11 cases. Extermination also worked on one occasion when it was tried in the Netherlands (Greaves, 1994). In cases where extermination failed, the resistance had evidently spread, undetected, into the surrounding population. Pilot schemes to exterminate the rat population in a larger area of 5 miles^2 in Wales and, later, to contain the resistant populations within a rat-free perimeter were also unsuccessful. The relative failure of these simple, attacking strategies was probably due to the limitations of the acute poisons that had to be used, shortcomings in organization and, most importantly, lack of biological insight into the nature of the problem.

Non-selective and counter-selective control techniques

Without question, the deployment of a suitable arsenal of alternative rodenticides is necessary for the management of resistance. Even outmoded compounds, such as zinc phosphide, were sufficiently active to prevent the problem from getting out of hand when anticoagulant resistance first developed in Britain. Newer rodenticides, to which 'practical resistance' has not yet developed, including the most recently developed anticoagulants brodifacoum, flocoumafen and difethialone, and the non-anticoagulants calciferol and bromethalin, all appear to be well suited for a role in resistance management.

A consistent selection differential that places resistant individuals at a disadvantage, large or small, is needed to eliminate resistance. The most practicable way to achieve this is first to stop using rodenticides to which the rodents are resistant, and then to erode the resistant population by the exclusive, persistent and, preferably, targeted use of non-selective or counter-selective control techniques, both chemical and non-chemical.

Restricting the availability of vitamin K to resistant rodents might be a sensible way forward. Green foodstuffs are known to be rich in vitamin K_1, and there is some evidence that maize silage can act as an antidote to anticoagulants (Jacob and Freise, 2011), although the vitamin K levels that occur naturally in the diet are normally considered too small to act as an antidote to any significant extent (Greaves, 1994). However, animal feeds are frequently supplemented with vitamin K_3 and, when they are not exposed to anticoagulants, this can effectively provide resistant rodents with a source of the vitamin. This removes the main pleiotrophic cost of resistance (i.e. the development of a vitamin K deficiency in homozygous resistant animals) but, in the presence of anticoagulant, vitamin K_3 does not act as an antidote in resistant and susceptible strains of Norway rats and house mice, presumably because the target enzyme, VKOR, is required to convert vitamin K_3 to the active hydroquinone. Restricting the availability of vitamin K_3 as a resistance management strategy, which has the virtue of reinforcing natural selection by utilizing the main deleterious pleiotropic effect of resistance has, so far, been neglected.

A contrary strategy, that of withholding (or 'saving') effective rodenticides while continuing to use a given anticoagulant until resistance exhausts its usefulness, is sometimes suggested as a means of retarding the development of resistance (Lodal, 2001). This course of action is precisely what might be recommended to accelerate the development and spread of resistance, and appears to stand logic on its head (Greaves, 1994).

The problem of resistance has been exacerbated in the European Union (EU) because of Directive 98/8/EC of the European Parliament and of the Council (EU, 1998), which has come to be called the Biocidal Products Directive (BPD). This has become the largest and most complex single regulatory initiative ever to affect the global market for public health pesticides (Buckle *et al.*, 2005), and has resulted in increased regulatory costs for maintaining products in the European market. As a result, many well-known rodenticides, such as zinc phosphide and calciferol, have been withdrawn from the market, and few rodenticides now remain that are not anticoagulants. Consequently, very few rodenticide formulations with an alternative mode of action are now available in the European market for the control of resistant animals (see Chapter 6).

'Practical resistance' to some second-generation anticoagulants

In the early 1990s, a resistance focus was discovered in north Berkshire (UK) where resistance to the second-generation anticoagulant, bromadiolone, resulted in an unequivocal treatment failure (Quy *et al.*, 1995). Prolonged applications of rodenticide with excellent bait consumption across the site had minimal effect on the rodent population. Animals trapped from this site were found to survive up to 26 times the susceptible bromadiolone LD_{50} dose.

Subsequently, similar treatment failures with the second-generation anticoagulants bromadiolone and difenacoum have been reported across central southern England, and analysis of animals trapped from these sites, using the *VKORC1* molecular resistance test, has revealed a high proportion of animals that are homozygous for the Leu120Gln mutation. The high frequency of this resistance genotype would indicate a very high degree of selection in these populations.

In several countries, such as the UK and Germany, the use of the more efficacious active ingredients brodifacoum, flocoumafen and difethialone is currently restricted to 'indoor use only', and can only be used against populations of rodents that predominantly live 'indoors' and in sewer systems. In most cases, this precludes their use against free-living Norway rat populations. Thus, populations of anticoagulant-resistant Norway rats exist that cannot be efficiently controlled using the rodenticides that are legally available (Buckle, 2013). There is also a tendency towards restricting the three highly potent active ingredients mentioned above to professional use only. Doing this will additionally impair the prospects of resistance management, as resistance-breaking compounds will become unavailable to consumers, leading to the increased use of compounds to which rodents are resistant, thereby promoting selection for resistance.

Evidence to date would indicate that resistant Norway rats possessing the *VKORC1* mutations Leu120Gln, Tyr139Cys and Tyr139Phe possess levels of resistance to either bromadiolone or difenacoum, or both, such that treatment using them may be ineffective (Grandemange *et al.*, 2009; RRAG, 2010; Endepols *et al.*, 2012; Buckle *et al.*, 2013). In such situations, continued use of these anticoagulants would exacerbate the resistance problem, and would pose an unacceptable risk to many non-target species (Buckle, 2013).

Resistance monitoring

When resistance has been detected and a resistance-management strategy initiated, monitoring is necessary to determine its effectiveness. The new molecular resistance testing methodology provides a practical and cost-effective way of achieving this on a broad scale. The occurrence of the resistance mutations can be determined from tissue samples collected in the field, thus negating the requirement to trap live animals and return them to the laboratory for testing. Tissue samples (e.g. a portion of the tail) can be collected from animals that have been freshly killed, but that have not died as a result of the anticoagulant treatment (to avoid selection of the more susceptible animals); these can be stored in 80% alcohol (not denatured) for delivery to the laboratory within 48 h, or stored at −21°C for later delivery. The genotyping of resistant Norway rats is progressing in Belgium, Denmark, France, Germany and the UK (Rost *et al.*, 2009; Grandemange *et al.*, 2010; Clarke and Prescott, 2011), with detailed geographical mapping of the mutations.

Monitoring implies a systematic, statistically designed and rigorous procedure, such as that described by Frantz and Padula (1980), by which rodent populations in the field are sampled for resistance testing in the laboratory. In the UK, the major driving force for resistance monitoring is the occurrence of populations of Norway rat that cannot be controlled with the rodenticides that are currently legally available to the pest-control operator (Buckle, 2013). If restrictions on the use of the more efficacious anticoagulant rodenticides are relaxed, there is, of course, the concern, as with the first-generation anticoagulants, that the goal of resistance management will recede, and no purposeful action will be conducted to eliminate known forms of resistance.

The Future

More than 50 years of experience with anticoagulant resistance has shown that it is a vain endeavour to try to prevent resistance from spreading. Provided the selective advantage is sufficiently strong, resistance will certainly remain and spread, once it has become established. There is, however, a good chance of delaying or retarding resistance development and spread, as long as effective active ingredients are available.

The anticoagulant burden on predators and scavengers is a matter of concern for environmentalists, and is primarily a result of the toxicity and persistence of the anticoagulants, in particular the second-generation anticoagulants. These compounds should, therefore, always be used wisely, with a resistance management strategy in mind. For example, in countries such as Germany, where anticoagulant resistance in Norway rats is still restricted to relatively small areas, there should be preferential use of the less persistent first-generation anticoagulants in areas where there is no resistance. In contrast, in countries such as the UK, where resistance is more widespread, it is essential to ensure that the only active ingredients used are those not affected by 'practical resistance', and molecular screening for the *VKORC1* mutations can play an important role here. At the same time, research should be intensified to understand more fully the primary and secondary non-target impacts of anticoagulants on wildlife.

Evolution of resistance

In the first edition of this book Greaves (1994) wrote: 'It is a philosophical proposition, based on the assumption that organisms are indefinitely variable, that resistance will inevitably evolve to all rodenticides if their use continues', and 'The alternative view is that new forms of resistance are unlikely, because a practical and theoretical limit is imminent'. Greaves (1994) also wrote this salutary warning: 'There are two certainties about the future. First, the unabated use of anticoagulants to which resistance has developed will unremittingly cause resistance to those compounds to spread. Second, the targeted use of compounds to which resistance has not developed will tend to eliminate or retard the spread of resistance to the first-mentioned compounds.'

Looking back over the last 20 to 30 years, when brodifacoum, flocoumafen and difethialone were used, there has been no real cause for concern. The only case in which reduced susceptibility to brodifacoum was encountered (Gill *et al.*, 1992), remained inconsequential. In contrast, when bromadiolone and difenacoum were introduced, it took only a short time for the first cases of resistance to be detected and, in some areas, these compounds fail to control resistant rats and mice. It would seem that in the short to medium term there is no reason to worry about the future efficacy of the more efficacious anticoagulants, provided that they are still available.

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10 Damage Assessment and Damage Surveys

A.P. Buckle
School of Biological Sciences, University of Reading, Reading, UK

Introduction

The practice of damage assessment in rodent control is much neglected. The tendency of researchers is to concentrate on the study of control technologies and, similarly, the attitude of those involved in practical rodent control leans towards the immediate implementation of management programmes. However, carefully planned and executed damage surveys provide immensely useful information (Judenko, 1973; Engeman, 2002). The reasons for conducting damage assessments may be considered under the following heads:

1. To establish the economic status of rodent pests, including justifiable expenditure on control and damage thresholds.
2. To determine the geographical distribution of pests, to assist decision making and to allow resources to be allocated where they are most needed.
3. To estimate the effectiveness of control measures, both on a small scale in experimental comparisons of different techniques and during large-scale management programmes.
4. To provide information for planning, for example in the distribution of pesticides and in the allocation of funds to research and development programmes in both the public and private sectors.

Walker (1983) provides an extensive review of crop loss assessment techniques and the uses to which the information generated can be put. Several textbooks also address this broad topic (Chiarappa, 1971, 1981; Govindu *et al.*, 1980; Harris and Lindblad, 1980), but rodent pests receive only limited attention in these.

The purpose of this chapter is to outline established methods for the assessment of damage and losses caused by rodents to certain growing crops and stored products. In the final section, some of the above-mentioned uses of the data are illustrated.

General Considerations

Sampling in damage surveys

On a small scale, it may be possible to identify all units, such as sacks of grain, stems of growing plants or bunches of fruit, that are at risk of rodent attack and to measure damage to them individually but, more often, this is not the case, and it is then necessary to choose a representative sample to exemplify the entire population under study. Great care is required in the choice of a sampling framework because this fundamentally influences the validity of data obtained.

It is strongly recommended that those intending to conduct damage assessments, for any purpose, should seek the advice of a statistician at an early stage, certainly before any extensive fieldwork is done. Several useful textbooks address this subject (Cochran, 1966; Snedecor and Cochran, 1967), and the work of Engeman (2002) offers sound advice about sampling frames for vertebrate pest damage assessments.

The sampling method least likely to impose bias is unrestricted random sampling. In this, each individual in the universe to be sampled is enumerated and has an equal chance of selection for assessment. Sample selection is often done by drawing lots or using random number tables. Random sampling is feasible in some stored commodities and in crops planted in rows, such as coconut and oil palm, but is impossible in densely planted crops, such as cereals and sugarcane. Alternatives to random sampling that are more practical in many circumstances include cluster, systematic and diagonal sampling. Each of these can be used with elements of randomization and has its own advantages and disadvantages; some of these are discussed in relation to rodent damage assessments by Rennison and Buckle (1988).

When conducting assessments in a single store or field, it may be possible to select the desired number of samples in one step, but when faced with a large and complex universe for assessment, a multistage, or stratified, sampling frame may be required. For example, a two-stage frame may be adopted in an oil palm estate: initially, a sample of fields is selected from those comprising the entire estate, and then another sample is taken of palms – within the selected fields – for the assessment of damage. At each stage, selection may be random or conducted in some other way.

Sample size and replication

The size of the sample selected has an effect on two important components of the assessment process: the precision of the results produced, and the effort required to obtain them. The objective should be to achieve the required level of precision with the minimum expenditure of effort. In this context, precision relates to the experimenter's confidence that the sample mean of the parameter measured in the survey operation lies within a predetermined range of the 'true' mean of the population sampled. Standard formulae are available for the determination of sample size for specified levels of precision (Rennison and Buckle, 1988). It is important to use these at the outset to avoid completing a survey, at great cost, only to find the data so imprecise as to preclude proper analysis. Some preliminary fieldwork is needed because, to apply these formulae, an estimation of the standard deviation (σ) of the parameter to be measured is required. Once again, the advice of a statistician is invaluable.

True replication is not usually conducted in conventional damage surveys, although some measure of experimental error is required if damage levels are to be contrasted, say, between different geographical areas. Replication is essential, however, when damage assessments are used in field trials to compare the efficacy of rodenticide treatments. There is an important point to note here. Most experimenters are now aware of the mobility of rodent pests and make allowance for this with appropriately large plot sizes for rodenticide treatments. With large plot sizes comes the temptation to conduct several damage assessments in subplots within each treated plot; these are not replicates in the true sense, because all were subject to the same treatment regimen and cannot, therefore, be treated as replicates for the estimation of experimental error in the analysis of results.

Relationship between damage estimates and yield loss

Damage assessments may be conducted in agricultural crops to obtain estimates of the monetary value of losses, but there is rarely a simple relationship between a measurement of rodent damage and yield loss. The nature of this relationship is discussed in more detail for each crop in the following sections. Damage assessments may both underestimate and overestimate the extent of losses. For example, it is well established that certain crops are able to compensate for damage inflicted by rodents, especially when damage is incurred at an early stage in crop growth (see Buckle *et al.*, 1979, for rice; Williams, 1975, for coconut) and, in this case, damage assessments may be overestimates of actual losses. In contrast, in crops that are in the field for extended periods, such as sugarcane and oil palm, an assessment is only a 'snapshot' of the damage currently visible and certainly underestimates final losses.

Several studies have sought to estimate real yield increases at harvest as a result of rodent pest management in field crops. Often it is found in these studies that the yield increases that are observed far exceed those that might have been predicted by damage assessments alone; see Wood (1971) and Buckle (1988) for rice; Reidinger and Libay (1980) for coconut; and Hampson (1984) for sugarcane.

Damage Assessment Methods for Key Crops

Rice

Nature of damage

Rice is susceptible to rat damage at all stages of growth (West *et al.*, 1975). Worldwide, the nature of damage is broadly similar, no matter where the crop is grown or what the damaging rodent species is.

Rice seeds and emerging seedlings are readily taken, both in nursery beds and when directly sown in the field, but few damage assessment methods take this into account. As the young plants grow away, the tillers develop soft stem bases that are particularly attractive to rodents. Stems damaged at this 'active tillering' stage sometimes appear to be cleanly cut when fresh, but later all that may remain is an accumulation of decaying fibrous tissue. Similarly, damage at the 'booting' stage is often ragged as a result of the rodents' attempts to gain access to the ensheathed, developing rice panicles at the bases of tillers.

After the 'heading' stage, rice stems have a tubular cross-section. These are cut by rodents to bring down the grain-bearing panicle. The way this is done by rats results in the typical obliquely cut stub which is characteristic of rat damage to rice, whatever the species inflicting it. When cutting tillers, the behaviour of rats is to bend the stem down and, with it held horizontally, to bite it through, eventually removing a section with a curved outline. When released, the stub springs back into place and, as it does so, it often tears away some epithelial fibres to produce a heel. Thus, rat-cut stems are readily identified and cannot be mistaken for those damaged by grazing animals such as goats and cattle, which usually leave a clean, horizontally cut stub.

The distribution of rat damage in fields is highly variable. When damage is light, cut tillers may be so widely distributed in fields as to be visually undetectable in cursory examinations. Moderate damage is often seen as patches of heavily damaged plants surrounded by areas of relatively light damage. In heavily attacked fields, the most common pattern of damage is one in which the centre of the field is almost totally destroyed, while the borders sustain little or no damage (Fig. 10.1).

These patterns reflect a situation where rat populations are comparatively sedentary, but the author has observed a different pattern, in which a 'wave' of damage appeared to move progressively across a rice field area over a period of several days. In that situation, literally hundreds of rats were seen at dusk to make unidirectional, simultaneous movements out of an area of dense undergrowth into fields of ripening rice. They reportedly made the return journey back to their harbourages before dawn. It was later discovered that the pattern of harvesting in neighbouring fields had probably systematically 'concentrated' rats from a wide area into a small patch of dense cover from which they foraged en masse: quite literally, a 'plague' of rats.

Fig. 10.1. Rat damage to maturing rice in Central Java, Indonesia. This pattern of attack is common in heavily damaged fields. The dark central patches are the remnant vegetative parts of the rice plants. The lighter areas of the fields at the periphery are where developing panicles remain. This farmer has lost more than 70% of his crop.

Damage assessment methods

The development of damage assessment techniques for rice took place mainly in South-east Asia where rice seeds are often sown in nursery beds prior to the transplanting of seedlings in the open fields. Seedlings are transplanted in groups of two or more, which grow to form rice 'hills', each comprising a number of growing stems (tillers) and separated from each other by a distance of 20–40 cm. These hills, therefore, provide natural sampling units for damage assessments in transplanted rice. Workers in several countries in the region devised sampling schemes for use in selecting rice hills in transplanted fields. However, direct sowing is now also popular, and modified sampling techniques are required for damage assessment in areas where this is practised.

In the Philippines, a systematic sampling scheme, with randomization, was used to select hills for damage assessment in fields of transplanted rice (Swink *et al*., 1974). In this scheme, the numbers of hills along the length and width of the field were first determined. Ten rows were then selected at random from the total number of rows in the field and ten rice hills were selected randomly from those in each row. Because the random numbers used to select hills in rows were the same, in effect, a grid was created with the hills situated at its 100 intersections. Each of the 100 hills was inspected for rat damage and the numbers of cut and intact tillers were recorded only in those with damage. An estimate of percentage damage for the field was calculated as follows:

$$\% \text{ damage} = ac/b + c \qquad (10.1)$$

where:
a = number of damaged hills;
b = number of undamaged tillers in the hills containing damage; and
c = number of damaged tillers.

This sampling frame provides excellent coverage of the entire field and the potential for information to be obtained from 100 separate sampling locations, but it is relatively time-consuming, because the field must be traversed ten times. These traversals bring with them the problem of inflicting damage to the crop, particularly if assessments are conducted close to harvest. The scheme also appears to be wasteful because much effort is expended in reaching hills and, when these are undamaged, they contribute little to the data obtained. The method is probably accurate where damage levels are moderate to high because, then, relatively large numbers of hills are assessed and used in the calculation of percentage damage. However, it may not be accurate when damage is very light, because the entire estimate is then based on measurements from a small number of damaged hills and error is introduced if these have either an abnormally low or high number of tillers. In such cases, it is possible to determine a minimum number of hills that is required to estimate, with a certain degree of precision, the percentage of damaged tillers (Cochran, 1966); with this modification, the method seems particularly appropriate for use in detailed field experiments.

An alternative method of sampling hills in rice fields was proposed by Rennison (1979). In this, a single diagonal transect is made of the field to be assessed. Of the two diagonals available, the one examined is chosen at random by the toss of a coin. The length of the diagonal is fixed at 150 rice hills. This may mean that, if the field is large, the surveyor may end short of completely traversing it. Alternatively, if it is small, the surveyor may find it necessary to cross the dyke into the neighbouring field to complete the 150 hill transect. The spaces between the 150 hills will mean that the surveyor will traverse an area of about approximately 0.2 ha. A total of 25 hills is chosen at random on the selected diagonal, with the gaps between selected hills being determined, in terms of a number of hills, from specially prepared random number tables (Rennison, 1979). Rennison (1979) proposed that the loss of ripe tillers at harvest, rather than percentage loss of tillers per se, should be the basis of assessment because it more closely reflects the loss of rice yield caused by rats. The number of ripe tillers is recorded in each of the sampled hills and the percentage of ripe tiller loss estimated as follows:

$$\text{\% ripe tiller loss} = 100(A - B)/A \qquad (10.2)$$

where:
A = ripe tillers per hill in undamaged hills; and
B = ripe tillers per hill in a 25 hill sample.

The relationship between this parameter and actual yield loss remains to be confirmed by experimental studies and, in a pilot survey using this method (Buckle and Rowe, 1981), difficulties were occasionally encountered in heavily damaged plots when all of the sampled hills were damaged. Also, in areas of severe damage, error is introduced when the number of ripe tillers per hill in undamaged hills is estimated from a very limited number of hills without damage.

An amalgam of these two methods presently represents the best combination of efficiency and reliability for use in rice rat damage surveys.

The single diagonal transect, with a 25 hill sample, should be adopted to reduce work and to limit damage to the growing crop caused by trampling. An unequivocal indicator of rat damage to the crop is the rat-cut tiller, and the number of cut and intact tillers should, therefore, be determined in each of the selected hills. The application of the following simple equation will then give the percentage of rat-cut tillers:

$$\text{\% rat-cut tillers} = 100\,(a/b) \qquad (10.3)$$

where:
a = number of rat-cut tillers in a 25 hill sample; and
b = total number of tillers in a 25 hill sample.

More work is required to determine the most cost-effective method to use, and a useful exercise would be to construct hypothetical, rat-damaged rice fields using a computer model. Different patterns of simulated damage, such as random and clumped, could be imposed. Data from real surveys would be necessary to provide information on the numbers of tillers in rice hills and the frequency of cut tillers in damaged hills. The damaged fields so constructed could then be sampled using the frames described above. The true level of damage would be known and, thus, the accuracy of estimates derived using the three assessment methods described could be ascertained.

The techniques discussed so far are appropriate only for areas where transplanted rice is grown and need some modification before they can be used in areas where rice is cultivated by direct sowing. In practice though, the only modification necessary is the replacement of the hill as the basic survey unit with a quadrat of a size likely to contain an equivalent number of tillers.

Salvioni (1991) used quadrats when assessing damage by *Rattus rattus* to direct-sown and transplanted rice in Madagascar. The 1 m square wooden frames were thrown about 2 m into fields and the numbers of undamaged and damaged tillers within them counted. Ten quadrats were assessed in each parcel of land surveyed and the percentage of rat-cut tillers calculated using Eqn 10.3.

Relationship between damage and yield loss

Studies in rice have sought to relate damage assessments directly to yield loss. Buckle (1988) recorded 7.5% rat-cut tillers in untreated plots at harvest in rice fields in Central Java, Indonesia, and a mean yield increase of 17% in equivalent plots provided with effective rodent control in which only 1.3% rat damage was recorded. This suggested that rat-cut tiller damage assessments conducted at harvest underestimated rice yield loss by a factor of about 2.7. In another study, Singleton *et al.* (2005) conducted rat damage assessments in rice in West Java, in areas following integrated pest management programmes. These authors also concluded that damage assessments substantially underestimated yield increases resulting from rat control and, based on damage and yield loss estimates, proposed that a ‘multiplier’ factor of 6.5 times be used to obtain estimates of yield loss from assessments of cut tillers measured near harvest time.

The timing of rat damage assessment in rice is not important if the data obtained are to be used only as indices of rat activity, for example in comparing different control techniques (see for example Buckle *et al.*, 1984b), but it is very important if the assessment is to be used as a measure of the effect of rat damage on rice yield. As demonstrated by the work of Buckle *et al.* (1979) and Singleton *et al.* (2005), a complex and dynamic relationship exists between the actual number of tillers damaged by rats, the number of these observable during assessment at any given time and the resultant yield loss (see for example Benigno, 1979).

The first, and perhaps the most obvious, factor affecting the relationship is that rat-damaged tillers decay, so that those attacked early in the growth of the crop become indiscernible at assessments conducted later. However, very little quantitative work has been done on this phenomenon. Undoubtedly, the soft stems of young tillers decay quite rapidly, whereas those of tillers after heading are strengthened by thickened vascular bundles and break down much more slowly.

The second factor, and one that has been the subject of much quantitative study, is the ability of rice plants to exhibit compensatory growth. Buckle *et al.* (1979) showed this capability to fall into three phases. At early growth stages, up to about 4 weeks after transplanting, plants compensate completely for damage involving the destruction of as many as 60% of growing tillers. This contrasts with the situation of damage inflicted during the ripening stage, say from about 12 weeks after transplanting to harvesting in modern varieties that ripen in about 120 days. At that stage, rice heads are fully emerged at the apices of tillers and yield loss is then directly proportional to the number of stems cut. Separating these two phases of ‘absolutes’, one of compensation and one of loss, is a phase in which some recovery occurs. However, the panicles produced by the compensatory tillers generally ripen too late to be harvested with the remainder of the crop. Thus, in damage assessments conducted during later growth stages, this growth is frequently seen as green, unripe panicles. These may be counted as healthy tillers rather than as rat-damaged tillers, but they actually contribute little to rice yield. It was an attempt to attribute these tillers to the ‘damaged’ category that caused Rennison (1979) to propose an assessment method based on loss of ripe tillers rather than on one restricted to counts of rat-cut tillers, and this approach certainly deserves further study.

The mechanisms of compensatory growth have been studied for stem borers (*Chilo* spp. and *Scirpophaga* spp.) by Rubia *et al.* (1996), and are likely to be the same as those for rat damage. These mechanisms include translocation of assimilates from damaged to healthy tillers, increased rate of photosynthesis, the production of additional tillers and increased grain weight.

A recent study of simulated rat damage in lowland irrigated rice in Vietnam (Nguyen *et al.*, 2010) produced similar results to those of Buckle *et al.* (1979), and included the proposal that it is cost-effective to implement rodent control in rice before rat damage reaches 10% cut tillers at the tillering stage. Studies made to simulate the damage of stem borers that were conducted with a knife or scissors result in exactly the same type of damage as simulated rat damage, and have provided similar results to those described above (Rubia and Penning De Vries, 1990).

Oil palm

Nature of damage

The damaging effects of rodents in oil palm plantations has long been recognized (Wood, 1976), and an account of rat damage to oil palms is given in Chapter 3. Seedlings in nurseries may be damaged if left unprotected, and young palms are vulnerable to attack for several years after transplanting. In these cases, damage takes the form of the consumption of the soft vegetative tissues and may result in the death of palms if the apical meristem is destroyed. Few surveys have focused on this type of damage, and no methodologies are established for its assessment, which is done readily by simple counts of healthy and damaged (or dead) palms.

The damage most commonly associated with rodents in oil palms is that related to their attacks on the fruit bunches (Fig. 10.2). Palms bear fruit throughout the year and these develop in large bunches, containing hundreds of individual fruitlets, in the axils of fronds. The palm trunks are easily climbed by rats to gain access to the fruit bunches, although there is some evidence that certain species are less adept at this than others. The rodents gnaw into and consume the fleshy, oil-bearing mesocarp at all stages of development, but ripe fruitlets appear to be favoured. Light damage to a palm may involve only small amounts of mesocarp tissue taken from a few fruitlets. When the damage is heavy, much of the valuable mesocarp may be taken and the rats may even penetrate the hard shell of the central nut to obtain the kernel. The mesocarp tissue is bright orange and, when damaged, retains this hue for 2–3 days. After that time, the cut surface dries and takes on a dull brown coloration. This allows old damage to be readily distinguished from fresh damage.

Fig. 10.2. Damage by *Rattus tiomanicus* to a ripe bunch of oil palm fruit in Malaysia. The valuable oil-bearing mesocarp has been eaten away down to the kernels of the fruitlets. The attacked tissues are bright orange when the damage is fresh but soon turn brown.

It has also been suggested that rats occasionally damage the male inflorescences of oil palms, but no assessment of the extent of this damage, or of its importance, has been done.

Damage assessment methods

No reliable method has been developed to extrapolate yield loss estimates from measurements of rat damage to oil palms (Chapter 3). Therefore, assessments are generally undertaken either in field trials to compare different control techniques (Chia *et al.*, 1990) or as a decision-making tool in oil palm rat management (Khoo, 1984). In both cases, the requirement is for information on existing infestation levels, and assessments are then usually restricted to the measurement of fresh damage.

Two methods are widely used. The first, and the most simple, is the assessment of the percentage of palms with fresh fruit damage. To obtain this value, palms are examined, scored as to whether any of their fruit bunches are freshly damaged, and the percentage calculated as follows:

$$\%\ \text{fruit damage} = 100\ (a/b) \qquad (10.4)$$

where:
a = number of palms with fresh fruit damage; and
b = number of palms assessed.

The second method is the assessment of the 'fresh damage score'. In this, the fruit bunches on each palm are separately enumerated. The level of damage sustained by each bunch is scored as light, moderate or heavy, and the data from all of the bunches assessed is used in the following equation:

$$\text{Fresh damage score} = \frac{(1\times a)+(2\times b)+(3\times c)}{3n}\times 100 \qquad (10.5)$$

where:
a = number of bunches with light damage (i.e. 1–3 damaged fruits per bunch);
b = number of bunches with moderate damage (i.e. 4–6 damaged fruits per bunch);
c = number of bunches with heavy damage (i.e. >6 damaged fruits per bunch); and
n = number of bunches assessed.

Assessments of fresh fruit damage are quick to carry out and easily standardized when several workers are to conduct them during a single trial. However, fresh damage score is the more sensitive estimator of rodent damage, particularly when damage levels are either very light or very heavy.

Estimates of yield loss

Yield losses caused by rodents in oil palm plantations can presently only be estimated by indirect means. To do this, rodent population density is first determined using standard capture–mark–recapture (CMR) methods (Wood, 1984). The number of rats per hectare is then multiplied by the quantity of palm fruits they are known to eat, derived from laboratory studies of rat feeding behaviour, to calculate the loss of oil-bearing tissue (Wood and Liau, 1984). Financial losses are then estimated using information on crop yields in the absence of rat damage and the quantity and value of oil expressed from the palm fruit. Some rodent species are known to be more voracious consumers of palm fruits than others and this must also be accommodated in the calculation (Wood *et al.*, 1987).

Coconuts

Nature of damage

As with oil palms, coconut seedlings are probably attacked by rats both in nurseries and when newly planted in their final positions in palm groves, but little is known of this type of damage. Rat damage to mature palms takes the form of holes gnawed in coconuts developing in the crowns of palms. The early work of Williams (1974a,b, 1975) on Fiji in the South Pacific is largely responsible for our understanding of this phenomenon.

Rats climb the boles of palms to reach the crowns and, perhaps because of some difficulty in doing so, attack short palms more readily than taller ones. Developing nuts are attacked close to the point of attachment to the inflorescence and a hole is made, typically about 65 × 40 mm (Fig. 10.3). Rats seem unable to penetrate nearly mature and mature nuts, and the majority of damage is, therefore, inflicted on those aged 3–6 months old. Damaged nuts remain in the palm crowns for only 3–5 days before falling to the ground. Even partially damaged nuts undergo abscission.

Rat damage to male inflorescences has also been reported to have a possible effect on pollen production, but Williams (1974a) considered the impact of this on coconut production to be negligible.

Damage assessment methods

As all coconuts fall to the ground within 1 week of being attacked by rats, counts of damaged nuts on the ground will accurately reflect the amount of damage inflicted up to within 1 week of the survey. However, damaged nuts are very slow to decay and, unless they are regularly cleared from the floor of the plantation, such counts will represent damage accumulated over a considerable, but uncertain, period of time. Williams (1974a) observed that, almost without exception, damaged nuts are green when they fall and slowly turn brown on the ground. This process was found to take 39 days for nuts of 3–8 months of age, with remarkably little variation. Therefore, any damaged green nuts found on the ground must have fallen within about 40 days of the survey and counts of these provide a useful quantitative measure for 'spot checks' of damage levels. Damaged nuts usually remain under the palms from which they have fallen and so this technique can be applied on the basis of individual palms. Williams recommended that at least 25 palms should be inspected at each survey location. He considered this method suitable for use by those wishing to conduct rat damage checks to determine the need for rodent control.

Fig. 10.3. Coconuts damaged by *Rattus exulans* on an island in the South Pacific. When the thick husk is perforated the nut remains on the tree for only a short time before falling to the ground.

Williams (1974a) used a second assessment technique to obtain more detailed information on rat damage to individual palms in palm groves over periods of up to 3 years. He collected all fallen nuts at fortnightly intervals and graded them both by size, in intervals of 5 cm, and by type, as follows:

1. With fresh rat damage, green coconuts with decay at an early stage.
2. With old rat damage, brown or dry coconuts with decay at an advanced stage.
3. With no rat damage, fresh green coconuts, a category including all other forms of premature nut fall.
4. Harvestable, coconuts usually cut for copra.
5. Others, mostly mature, barren nuts.

From these observations, Williams was able to estimate rat damage levels during fixed time periods using the following formula:

$$\%\ \text{rat-damaged nuts} = 100\ (a/b) \quad (10.6)$$

where:
a = number of rat-damaged nuts; and
b = total number of harvestable and rat-damaged nuts.

Relationship between damage and yield loss

Williams (1974a) made a remarkable observation in his long-term study plots. He partitioned palms according to the levels of damage they sustained, monitored nut yields and found that there was no apparent difference in yield between palms that sustained low and high levels of damage. Furthermore, in a trial where damage was simulated (Williams, 1974b), female flower production increased in damaged palms.

This response to the loss of developing nuts resulted in compensation for an estimated 50% of those lost due to rat damage. Williams (1974a) proposed that a correction factor should be applied so that counts of fallen rat-damaged nuts are halved to arrive at an estimate of yield loss. He did postulate, though, that damaged palms may be the most vigorous and that, in the absence of rat damage, these would have produced more nuts than the less vigorous plants which sustained little damage. This implies an ability of rats to select palms for damage. It is difficult to propose a mechanism for this, although rats do select the softest nuts on which to feed, because these have the highest concentration of sugar.

Further information was provided on the damage versus yield loss relationship in coconuts by the study in the Philippines of Reidinger and Libay (1980). They worked in a coconut plantation in which the owner had a record of yields from individual plants and their data provided information that casts doubt on some of the conclusions of Williams (1975). Crown baiting was effective in reducing damage by *Rattus rattus mindanensis* (now *Rattus tanezumi*) and *Rattus exulans*. However, measured yields in treated plots were 2.5 times greater than those from the same plots prior to the implementation of rodent control. This observation was in marked contrast to damage assessments, conducted by counting fallen rat-damaged nuts, which ranged from 4.5 to 5.8%. Reidinger and Libay (1980) also observed the effects of rodent control on increased yields in untreated 'control' plots that were at least 150 m away, indicating that rats entered treated plots from a considerable distance to take bait (see Chapter 8). This work appears to show that, for coconuts at least, damage assessment may greatly underestimate actual yield losses.

Maize

Nature of damage

Maize seed is usually sown directly into fields, either by hand or by machine drilling, according to the sophistication of the available production technology. Rats commonly dig up and consume both seeds and developing seedlings. Light damage of this type is mostly ignored by farmers, as it merely leads to a patchy crop, but heavily damaged fields may require resowing after some form of rat-control programme has been implemented. The soft stems of the young maize plants are also vulnerable and highly attractive to rats, although their loss does not necessarily have a direct effect in reducing crop yields (see Judenko, 1967).

The type of damage most commonly reported by crop protection workers is that inflicted by rats to the developing maize cobs (ears). Large rodent species, such as *Thryonomys swinderianus* in West Africa and *Bandicota* spp. in Asia, chew through the maize stems at, or near, ground level and fell them to obtain the developing grain. These stems are relatively robust, though, and the more agile rodent species, such as *Rattus* spp. and, in Africa, *Arvicanthis niloticus* and *Praomys natalensis*, are able to climb them to attack the cobs *in situ*. Cobs damaged by the latter method may be completely destroyed but, more often, they are only partially damaged. Hoque *et al.* (1986a) identified two types of partial damage to maize cobs in the Philippines (probably inflicted by *R. r. mindanensis)*. In one, damage was confined to the removal of kernels in strips down the longitudinal axis of the cob and, in the other, the kernels were taken in rings around the circumference.

The distribution of damage within maize fields probably depends on local conditions, even if there is little doubt that areas close to other infested crops, or to land offering harbourage to rodents, are more prone to attack.

Damage and yield loss assessment methods

Work in the Philippines has provided an excellent basis for damage and yield loss assessments in maize. The early work focused on a comparison of techniques for sampling plants in rat-damaged maize fields (Hoque *et al.*, 1986a). To start with, all of the maize plants growing in two fields, each about 0.5 ha, were assessed for rat damage; thus, the absolute level of rat damage in the fields was known. These assessments comprised counts of the numbers of damaged cobs and an estimate of resultant yield loss derived from established regression equations relating measurements of the size of the damaged portions of cobs and actual loss of yield of shelled kernels. Three different sampling techniques were then applied in the fields; the objective of each was to sample about 5% of the maize hills present. The first, the *random* method, involved the random sampling of 23 hills in each of 23 randomly selected rows. (Note: this is not unrestricted random sampling because, once the rows for assessment are chosen, hills in all other rows cannot be selected.) In the second technique, the *random quadrat* sample, a total of 21 quadrats (five hills × five hills) was selected, their positions in the field being determined at random. The third technique, the *strip systematic* method, involved the selection of 60 strips, each comprising two rows by five hills, using a *systematic* sampling frame.

The mean damage levels estimated by these three methods did not vary significantly either among themselves or between them and the true level of damage. Similarly, the sample variances differed little, although the strip systematic method gave estimates that were closest to the true levels of damage and was by far the least time-consuming to conduct.

Further work was conducted to refine the method of estimating actual yield loss from measurements of the dimensions of damage to maize ears (Hoque *et al.*, 1986b). The following equations were derived for circular and strip damage types respectively:

$$\log Y_c = 1.15 + 0.95X \qquad (10.7)$$

where:
Y_c = common logarithm of grain loss per damaged ear (circular damage type); and
X = ratio of damage area (cm^2) to ear length (cm).

$$\log Y_s = 0.83 + 0.15X \qquad (10.8)$$

where:
Y_s = common logarithm of grain loss per damaged ear (strip damage type); and
X = ratio of damage length (cm) to ear length (cm).

The authors went on to recommend a stratified sampling frame for selecting fields when conducting large-scale crop loss assessments. They also recommended the use of the strip systematic scheme for sampling hills in fields to determine the number of damaged ears and the use of the above equations on samples of ten ears of each damage type to estimate yield loss in the chosen fields. Hoque *et al*. (1986b) consider, with justification, that these proposals provide all requirements for the assessment of losses caused by rats in maize. However, they recommend that assessments should be done within 2 weeks of the intended date of harvest and, therefore, these techniques assess losses only of developing cobs and do not assess damage to the vegetative stages of the crop. Possibly this is less important than it seems at first, because Judenko (1967) showed that undamaged developing maize plants compensate with increased yield when their neighbours are destroyed by rats.

Sugarcane

Nature of damage

Sugarcane is susceptible to rat damage at all stages of growth, though many authors have reported that rats prefer to infest mature fields, presumably because of the high sugar content of the canes at that time. Rats of all cane-infesting species inflict damage of a similar nature; they gnaw through the rind of canes to obtain the sugar-bearing cortical tissue, principally in the areas of the internodes (Fig. 10.4). While the canes remain standing, damage may be limited to the first two or three accessible internodes, but if the canes fall, all of the internodes of a cane may be damaged. There are many reports that rat damage leads to secondary infection of canes with bacterial and fungal diseases.

Fig. 10.4. Sugarcane is susceptible to rat damage wherever it is grown. Damage assessments are usually based on counts of damaged internodes. However, the tissues exposed after attack are quickly infected by microorganisms, such as fungi, and this adds a further yield-reducing component to the primary loss caused by the consumption of sugar-bearing cortical tissue.

Damage assessment methods

Many different methods have been described for the assessment of rat damage to sugarcane and no single technique has been established as preferred over the others (see Hood, 1968; Porques and Ledesma, 1970; Lefebvre *et al.*, 1978; Flotow, 1980). The method of Hamelink (1980) is a systematic sampling scheme with randomization and seems as good as any. The first step is to identify ten rows of cane hills in which rat damage counts will be conducted. The number of cane rows in the field is counted and divided by ten. The product, for example 15 in a field of 150 rows, is the distance, in rows, between rows to be assessed. A number, randomly selected between 1 and 15, determines the distance from the corner of the field to the first row of the ten to be sampled; the remaining rows are chosen systematically at 15 row intervals. Next, the row length is measured approximately by pacing it, and a random number selected between one and the result. This number represents the distance from the field margin, in paces, of the initial point of a strip of 30 canes to be assessed for damage. Care is needed to ensure that the selected section does not run off the end of the row. Internodes in the first of the ten strips of cane are then recorded in the following categories:

1. Undamaged.
2. Top damage (damage in top half of cane).
3. Bottom damage (damage in bottom half of cane).
4. Old rat damage.

This procedure is repeated in each of the other nine selected strips and an estimate of damage is then calculated as follows:

$$\%\ \text{damaged internodes} = 100(a/b) \quad (10.9)$$

where:
a = total number of internodes in classes 2–4; and
b = total number of internodes in 300 cane sample.

It is not necessary to count all undamaged internodes, and the following procedure is intended to save time when damage is very light. In this case, all damaged internodes are counted on 30 canes, as above, but a sample of only five canes in each of the ten strips is used to estimate the number of internodes in canes. The value of *b* then becomes the average number of internodes per cane, estimated from the 50 canes counted, multiplied by 300. It would then be a simple matter also to express these data in terms of the percentage of canes with damage.

Relationships between damage and yield loss

Hamelink's estimate of damage clearly has little direct relationship to yield loss because, among other constraints, not all sugar-bearing tissue is removed by rats in damaged internodes. Furthermore, damage is known to affect both the weight and the sugar content of cane. Many workers have, therefore, attempted to establish the relationship between their particular estimate of damage and the loss of yield by some further process of calculation. Hampson (1984) reviewed these studies and summarized them with the conclusion that direct correlation is very difficult because of other, unrelated factors that affect yield, such as variety, rainfall, soil fertility, weed control, and the incidence of other pests and diseases. However, there was good agreement among some of the cited studies in the relationship between the percentage of canes with damage and sugar loss. When 10% of canes were damaged, for example, sugar losses in five studies ranged from 3.1 to 4.2%, with a mean of 3.7%.

Hamelink (1980) determined the loss of sugar caused by the four damage classes (n_i) outlined above and derived the following 'correction factors' (f_i) for the four damage categories: class 1 = 0; class 2 = 0.0316; class 3 = –0.0105; and class 4 = 0.1790. These correction factors are used in the following equation:

$$\%\text{ yield loss} = \frac{(n_1 \times f_1 + \ldots\ldots n_4 \times f_4)}{N} \times 100 \quad (10.10)$$

where:
n_i = sum of damaged internodes per class (i = classes 1–4);
f_i = correction factors for sugar loss (i = classes 1–4); and
N = sum of all internodes (i.e. $n_1 + n_2 + n_3 + n_4$).

It is noteworthy that damage at the bottom of canes appears to increase, rather than decrease, sugar yield. Hamelink pointed out that these relationships should be derived anew at each survey site until there is confidence that more generally applicable correlations have been developed.

Once again, these assessments are carried out within a few weeks of harvest to minimize the effect of damage between assessment and harvesting. Therefore, they do not take into consideration damage done to canes during the early stages of stool establishment and tillering.

Cocoa

Nature of damage

Rodents, both rats and squirrels, are serious pests of cocoa, and detailed studies of the damage they inflict have been undertaken in many countries, including Nigeria (Everard, 1964), Fiji (Williams, 1973), Malaysia (Han and Bose, 1980) and Equatorial Guinea (Smith and Nott, 1988). Generally, these studies have concentrated upon damage to ripening and ripe cocoa pods, but Everard (1964) remarked that germinating cocoa seeds in nurseries and young plants in the fields may also be destroyed.

All of these authors have noted that pod damage is almost entirely restricted to ripe fruit. The tough husks are gnawed through to create a jagged hole, the beans are taken out, and their surrounding mucilage scraped off and eaten. The beans themselves are usually discarded and are found on the ground below the damaged pod. Several authors have claimed the ability to distinguish between rat and squirrel damage by the positions of the holes made in the pods, by the dimensions of these holes and the sizes of pieces of pod wall removed to create them, and by the shape and size of the marks left by the rodents' incisor teeth (Everard, 1964; Kamarudin and Lee, 1981). The disease black pod, caused by fungi of the genus *Phytophthora*, is almost universal in cocoa plantations and quickly infects damaged pods. Even pods only superficially damaged by the claws of rodents as they clamber among the trees become infected, and this contributes further to the losses caused.

Damage and yield loss estimates

Because all damaged pods are completely lost, and damage is almost entirely restricted to ripe pods, assessment of the number of damaged pods serves as a direct measure of yield loss. Smith and Nott (1988) proposed a scheme for measuring pod damage. The situation in their survey was complicated by the presence of seven different damaging species: three true squirrels, two flying squirrels, a porcupine and a cricetomid rat. Assessments were conducted in plots of 1 ha, each containing about 900 trees. A systematic sampling scheme was adopted in which every fifth tree in every fifth row was examined, giving a total of 49 trees per plot. Ripe pods were categorized as: (i) undamaged; (ii) with scratch marks; (iii) bitten, but appearing to be recently ripened; (iv) old and damaged, where the whole pod had turned black. For purposes of the assessments, each tree was divided into three regions reflecting the types of damage done by the different rodent species: (i) the trunk up to 1 m from the ground; (ii) the rest of the trunk; and (iii) the branches. Young, unripe pods were considered not susceptible to damage and were ignored, and old, blackened and damaged pods were excluded from yield loss estimates. The percentage of damaged pods was calculated as follows:

$$\%\text{ damaged pods} = 100\,[(b + c)/(a + b + c)] \qquad (10.11)$$

where:
a = undamaged pods;
b = scratched pods; and
c = freshly bitten pods.

A number of assumptions were made in relating damage directly to yield loss.

- Pods bitten or scratched will be completely lost to black pod disease.
- Damage at the different levels in trees can be recorded with equal accuracy.
- Pods attacked by rodents are not completely consumed or removed.

It was considered unlikely that any of these assumptions was fully satisfied, but that the data acquired were robust enough to provide useful quantitative estimates of the extent of crop losses. Losses of ripe pods were estimated to be in excess of 40% in 1 year.

Stored products

Nature of damage

The damage inflicted by rats and mice to stored commodities has been fully described elsewhere (Chapters 2 and 11). In summary, rodents consume foodstuffs destined for humans and domestic animals, cause physical damage to packaging and other types of container, and contaminate products with hair, urine and faeces.

Damage assessment methods

The measurement of losses caused by rodents to stored products per se is a difficult undertaking (Jackson and Temme, 1980), and the great variety of materials stored and the many different storage systems make generalization equally difficult when describing the methods available. Some of the possible approaches are exemplified by Greaves (1980) and Hernandez and Drummond (1984).

An easily obtained assessment is the number of stores infested. This information comes from careful surveys of stores for the presence of rodents. Signs of infestation sought when conducting such surveys include burrows, droppings, footprints, damage to the commodity stored and smears. If this assessment forms part of a survey of many storage structures, the information obtained can be expressed as the percentage of stores infested. When stored commodities are destined for human consumption, this information may be all that is required to demonstrate the need for a control programme because, in many countries, such infestation is not tolerated. No information is generated, however, on the value of losses.

Another approach first involves the determination of the numbers of rodents infesting the store (Greaves, 1980). Well-established techniques are available for this purpose and include either a complete 'trap-out' of all infesting rodents or, if trap-out is impractical, population estimation using CMR techniques (Chapter 8). Both of these methods provide information on the numbers of rodents present, their species, and the age and weight distributions of the individual rodents comprising the infestation. These data are then used to calculate the quantity of stored produce consumed by the infestation on a daily basis. This is done using information on the quantity of the stored food eaten by rodents, either derived from laboratory studies of individually caged rodents or using the assumption that rodents with body weights greater than 50 g eat an average of 7% of their body weight in dry food daily and this figure is 15% for animals weighing 50 g or less. The following equation is applied separately for each infesting species to calculate the amount of stored food consumed:

$$\text{Weight of food consumed (g)} = P\,[0.07ab + 0.15(1 - \alpha)c] \qquad (10.12)$$

where:
P = population estimate;
a = proportion of the population of body weight >50 g;
b = mean body weight (g) of rodents weighing >50 g; and
c = mean body weight (g) of rodents weighing <50 g.

This method is particularly appropriate for the assessment of losses to commodities stored in bulk, but it does not take into consideration damage to packaging materials such as gunny sacks and boxes, and it also makes no allowance for the cost of the cleaning of produce contaminated by rodent excreta and hairs. In both cases, the financial losses inflicted may far outweigh the value of the commodity lost by direct consumption.

Hernandez and Drummond (1984) conducted loss assessments in a number of warehouses in Cuba. These were infested with all the three cosmopolitan rodent species: *R. norvegicus*, *R. rattus* and *M. musculus*. A wide variety of human foods was stored in the warehouses, generally in small packs destined for retail distribution. Products came to the warehouses as large single-commodity loads and left it as smaller mixed loads. As departing loads were assembled, their components were rigorously checked for rodent damage. The weight of produce lost was carefully tallied; this process was assisted by the fact that all packs damaged or soiled by rodents were considered to be a complete loss. Losses were expressed in terms of their monetary value over fixed time periods, and amounted to about 1% of the value of the produce stored. This exceeded by far the cost of the rodent-control measures subsequently applied.

These approaches serve to illustrate some of the methods used in the assessment of stored products losses. They represent practical attempts to measure the damage inflicted by rodents in stores in quantitative terms. They have shortcomings, but they are better than the 'guestimates', generally made from behind a desk, that litter the literature on this subject.

Uses of Damage Survey Data

The foregoing sections outline a number of techniques for the assessment of damage to growing crops and stored products. Engeman (2002) discussed the uses and misuses of damage assessment data and warned that damage assessment methods must be well designed and cost-effective if they are to provide data that allow sensible crop protection decisions to be based upon them. He particularly noted the importance of knowledge of the relationship between damage and yield loss, which has been the subject of much of the foregoing.

Generally, the importance of the information afforded by damage assessments is self-evident. Nonetheless, some illustration of their value is worthwhile here, particularly where data have been used in an innovative way.

Establishing the economic status of rodent pests

A broad definition of a pest is 'a living organism which causes damage or illness to Man or his possessions or is otherwise, in some sense, "unwanted"' (Conway, 1981). However, most people now involved in pest management would also expect a definition to give consideration to the economic significance of the damage caused.

A simple model was proposed by Dolbeer (1981), which allows an estimate to be made of the justifiable cost of pest-control measures. He expressed this cost (Y) as a function of X, the monetary value of potential losses, and b, a constant representing the proportion of the potential loss saved by the control measure. Two relationships are readily apparent. First, justifiable expenditure is greatest when the value of X is greatest and when b, an alternative term for the efficacy of the control measure, is also at its maximum value. Second, there is a net gain only when bX is greater than Y. In other words, there is a threshold damage level below which control ceases to be economically justified. The economic injury level (EIL) can be derived from these relationships, and may expressed as a percentage loss of crop or stored commodity (Buckle *et al*., 1984a; Brown *et al*., 2007), as follows:

$$T\% = 100\ (Y/bX) \tag{10.13}$$

where:
T = economic injury level;
Y = cost of control;
X = value of potential loss; and
b = a constant representing the proportion of the potential loss saved by the control measure.

Kamarudin (1983) used these relationships to examine the cost-efficacy of rodent control in cocoa plantations in Malaysia. He estimated the value of crop loss at the EIL (i.e. when $Y = bX$), and converted this into a number of cocoa pods by dividing X by the current market price of pods. He considered the absolute number of damaged pods to be a better parameter for use in decision making than the percentage of damaged pods (Williams, 1973), because substantial fluctuations in pod density occurred during the annual crop cycle.

Brown *et al*. (2007) worked on house mouse damage to wheat in Australia (Chapter 12) and derived the EIL for this scenario. They used a modelling approach, with an agricultural product systems simulator (APSIM), to obtain outputs that included the relationship between yield loss and the size of mouse populations. The EIL in this case was very low (2.6% yield loss when control is 95% effective). This novel approach to damage assessment, rodent populations, cost of control and yield loss holds much promise for use in other crops and with other rodent species.

Determination of the geographical distribution of pests

Surveys to determine the presence or absence of a pest species serve to demonstrate the potential for damage and loss to occur within a given geographical area. Augmented by an estimate of population density, this information can be used to calculate the value of pest losses, provided the relationship between pest numbers and the losses they inflict is known. This technique is used for rodents in stored products (Greaves, 1980) and in oil palm plantations (Wood and Liau, 1984), but elsewhere is largely impractical.

The use of this method is impossible, for example, in rice fields in South-east Asia, because the most common pest species, *Rattus argentiventer*, is not amenable to CMR techniques used in population estimation. Instead, damage assessments are undertaken and used to determine the distribution of the pest and the need for control measures. For example, Buckle and Abdul Rahman (1978) conducted a survey of rat damage to the 17,000 ha rice field area in Penang State, Malaysia. The state is divided into three administrative districts (Northern, Central and Southern), and these provided the first stratum of the sampling frame. A total of 27 sampling units of uniform size, covering all rice areas, were allocated to these districts in numbers proportional to their areas planted with rice. Three rice fields were selected at random from those within each sampling unit and 100 rice hills were selected in each field, using a systematic scheme with randomization. The numbers of damaged and undamaged rice tillers were counted in each hill. The results are summarized in Table 10.1.

Rat damage was not evenly distributed throughout Penang State. Analysis of variance of arcsine transformed percentage damage data showed that damage was significantly greater in the Northern District than in the Central and Southern Districts. Indeed, more than 85% of total damage was found in the Northern District, which comprised less than 50% of the state's rice field area. Clearly, control programmes would be more cost-effective there than in the other two districts. The survey data were further used to estimate the value of rice losses inflicted by rats during the 1978 'off season'; this was 1.68 million Malaysian dollars (US$1.00 = M$2.60).

Damage assessments can be further used in making decisions on the need for rodent control in specific growing areas. Sequential sampling schemes, for use by individual growers, have been developed for rice (Rennison, 1979; Buckle, 1988) and oil palm (Khoo, 1984). In these cases, action thresholds are used rather than the EIL. These action thresholds are set at lower levels of damage than the EIL because of the time which must elapse between the damage observation and the implementation of remedial control action.

Estimating the effectiveness of control measures

Damage assessments frequently play a part in measurements of effectiveness of rodenticide treatments in field trials. In this case, they may be used as specific indicators of comparative rodent activity between treated and untreated plots. For example, Chia *et al.* (1990) used assessments of fresh fruit damage to monitor the effectiveness of control techniques on plots with and without anticoagulant rodenticide treatments in oil palm plantations. They substituted data on the percentage of palms with fresh damage into the formula of Henderson and Tilton (1955) to derive estimates of percentage efficacy. As an additional efficacy assessment method, they also radio tracked rats on an untreated plot and on one treated with brodifacoum. They showed that levels of fresh damage closely reflected the actual numbers of rats alive on the plots, thereby confirming the value of the damage assessments in population estimation (Fig. 10.5). Similar assessments were a key component in the estimation of efficacy of pulsed baiting treatments in rice fields (Buckle *et al.*, 1984b) and in many other field trials of rodenticides.

Providing information for planning control campaigns

The distribution of rat damage in a crop or commodity to be protected by a control programme has an important influence on how the programme is to be managed. For example, if damage is evenly distributed, the treatment of one unit will have no particular benefit over the treatment of any other. However, more often than not, rat damage is not uniformly dispersed and, as shown above,

Table 10.1. A summary of survey data of rat damage to growing rice in three administrative districts of Penang State in the off-season crop of 1978. (From Buckle and Abdul Rahman, 1978.)

District	No. sampling units	No. fields	No. total tillers counted	No. rat-cut tillers	% Rat-cut tillers
Northern	16	48	77,150	7758	10.06
Central	8	24	34,829	943	2.71
Southern	3	9	12,641	397	3.14
Total	27	81	124,620	9098	7.30

a damage survey will allow the areas at greatest risk to be identified. Information from such surveys can be further used to examine the effects of decisions taken during the planning of control programmes.

Buckle *et al.* (1984a) conducted rat damage surveys over three seasons in Penang State, and plotted the observed frequencies of survey units with different damage levels. These frequencies are given in Table 10.2 (column 2), converted into percentages of the total number of survey units (column 3) and accumulated (column 4). The numbers of rat-damaged tillers in each class (column 5), an indicator of the level of rat damage, are also transformed to percentages of the total number of damaged tillers (column 6) and accumulated (column 7). The cumulative percentages in columns 4 and 7 are plotted against damage levels to obtain information that is useful in planning a control programme (Fig. 10.6).

The EIL for rice rat control was calculated to be between 0.48 and 0.97%, depending on whether the assumption was made that control methods are either 50 or 100% effective. The data given in Fig. 10.6 allow the effects of implementing these thresholds to be predicted in terms of the area of rice fields that would require treatment, and the proportion of the total damage sustained that would be alleviated. It seems likely that, in both cases, the extent of the treatments would probably be beyond the resources of the money and manpower available. Let us suppose, then, that sufficient resources existed to treat 20% of

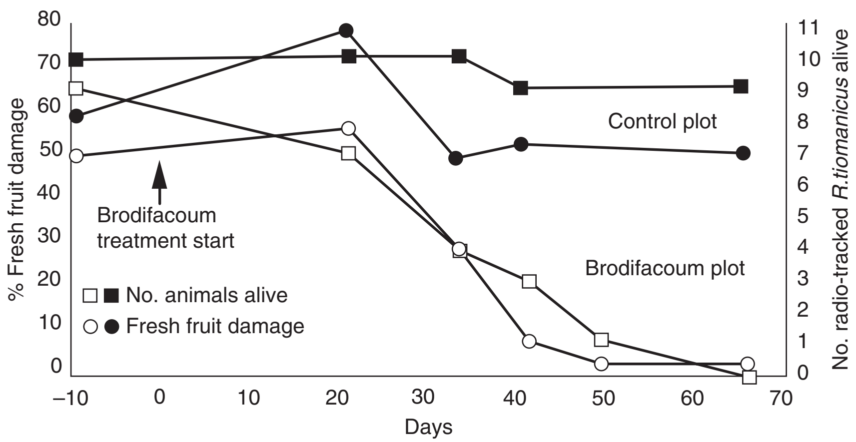

Fig. 10.5. Survival of radio-tracked *Rattus tiomanicus* and levels of fresh fruit damage on brodifacoum-treated and control plots in oil palm plantations. (From Chia *et al.*, 1990.)

Table 10.2. Pooled rat damage data for three growing seasons from Penang State, Malaysia. (From Buckle *et al.*, 1984a.)

Damage class (%)	No. survey units	% Total survey units	Cumulative % total survey units	No. damaged tillers	% Total damaged tillers	Cumulative % total damaged tillers
0–1.9	14	20.6	20.6	697	3.5	3.5
2.0–3.9	21	30.9	51.5	3211	16.0	19.5
4.0–5.9	14	20.6	72.1	3639	18.1	37.6
6.0–7.9	6	8.8	80.9	2335	11.6	49.2
8.0–9.9	2	2.9	83.8	886	4.4	53.6
10.0–14.9	4	5.9	89.7	2207	11.0	64.6
15.0–19.9	4	5.9	95.6	3090	15.3	79.9
20.0–29.9	3	4.4	100.0	4053	20.1	100.0
Totals	68	100.0	–	20,118	100.0	–

the rice field area. Figure 10.6 allows the impact of this strategy to be predicted. A damage threshold of about 10% would need to be implemented and almost 50% of the total damage sustained would be alleviated.

Finally, damage assessment data can be used to predict the cost and benefits of implementing rodent-control schemes. This information is valuable to those attempting to attract funding either from national or international agencies. Table 10.3 shows how the information from the Penang rice rat damage surveys can be used to perform this function.

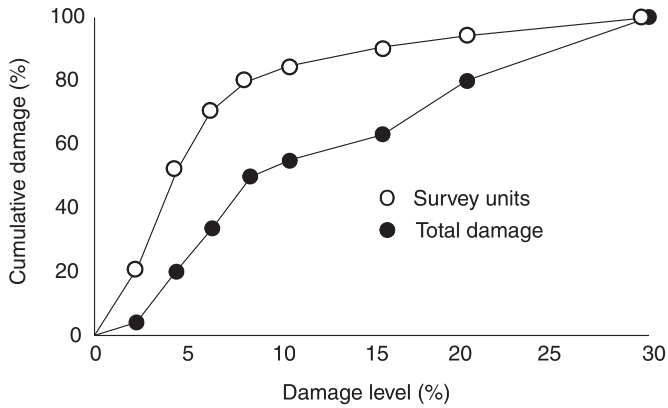

Fig. 10.6. Cumulative frequency distributions of data on rat damage to rice from surveys over three seasons in Penang State, Malaysia. The higher curve represents the cumulative percentage of survey units in the sample that had levels of damage less than or equal to the value indicated on the *x*-axis. The lower curve represents the cumulative percentage of the rat-cut tillers in the surveyed area that occurred in survey units that had levels of damage less than or equal to that indicated on the *x*-axis (from Buckle *et al*., 1984a).

Table 10.3. Benefit–cost analysis for rat control treatments in rice fields in Penang State, Malaysia.

	Main-season crop	Off-season crop	Both seasons
Area planted (ha)[a]	16,326	15,196	31,522
Actual yield (kg ha^{-1})[a]	3161	3304	3230
% rat damage[b]	8.3	6.2	7.3
Potential yield (kg ha^{-1})[c]	3447	3522	3484
Potential value of harvest (M$ million)[d]	22.51	21.41	43.93
Estimated yield loss (M$ million)[e]	1.87	1.33	3.21
Area requiring treatment (ha)[f]	9541	8881	18,422
Cost of treatment (M$)[g]	62,969	58,615	121,585
Potential saving (M$ million)[h]	1.67	1.19	2.87
Actual saving (M$ million)[i]	0.84	0.60	1.44
Benefit:cost ratio	13:1	10:1	12:1

[a]Data from published figures.
[b]From Buckle and Rowe (1981).
[c]Actual yield × 100/(100 – % rat damage).
[d]Farm gate price of rice M$0.4 kg^{-1}.
[e]Estimate of rat damage at harvest assumed to be equivalent to yield loss.
[f]Assuming 3% threshold and damage distribution as in Table 10.2.
[g]Includes (i) cost of bait and (ii) cost of baiting.
[h]89.5% of estimated yield loss (see Fig. 10.6).
[i]Assuming 50% reduction of yield loss following treatment.

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11 Rodent Control in Practice: Protection of Humans and Animal Health

A.N. Meyer[1] and D.E. Kaukeinen[2]
[1]*Acheta, Chieveley, UK;* [2]*Wilmington, Delaware, USA*

Introduction

The term 'commensal', when applied to a rodent pest, suggests that the animal is living 'off man's table'. The implication is that these commensal species thrive best when living closely with humans or in environments that are made by humans, with these environments potentially providing the food, the water and the physical environment that the rodents require to survive. The problems and the conflicts caused by the development of rodent infestations have been covered in earlier chapters of this book (Chapters 2–4). The severity of these conflicts will vary greatly but, as a general rule, the conflicts will be most severe where there are most rodents and where maximum rodent numbers coincide with maximum human and livestock density.

The problems caused by rodents are wide ranging. Attempts to quantify damage and losses inevitably fail to do anything but confirm the variability of the problem and the difficulty of measuring losses caused by mobile species in dynamic environments (Chapter 10). In order to obtain some idea of the complexity of the issue, the problem areas need to be considered individually. Broadly, damage and losses may be attributed to the following areas:

1. Disease transmission.
2. Direct consumption of food.
3. Damage and contamination of food and feed.
4. Structural damage.
5. Costs associated with control operations.
6. Phobias and adverse personal reactions to rodents.

The first five of these factors were considered in Chapter 5. An additional 'loss' of particular relevance to rodent infestations of municipal and household premises is caused by phobias associated with rodent infestation.

Few people actually enjoy the presence of wild rodent infestations and most would prefer to see the rodents controlled. In some instances, people have such strong rodent phobias that they find it impossible to live with active infestations, with some having to move house to avoid such possibilities. Some of those who have such phobias suffer with stress and poor health when faced with rodent activity. These costs, while perhaps not nationally very high, can be very important to individuals. In some cases, the very fact that a building may be infested with rodents or may have been infested in the past, but now may be clear, will be sufficient to make such people move out of the building either temporarily or permanently. Sometimes, the home is sold, at great cost, simply to avoid living with the memory of infestation.

Rodent-control Strategies in Municipal and Householder Premises

An important issue here is that, before any rodent-control operations are undertaken, it is essential that those undertaking the control know exactly what it is that they are dealing with and can measure the levels of success that they will achieve. One of the difficulties encountered by those undertaking rodent control over the decades has been the practical problem of measuring the levels of infestation and identifying the patterns of distribution of the rodent problem. Only by doing this can the relative risks of infestation in different environments be measured and limited control resources targeted and used most cost effectively. This procedure will apply to all rodent-control operations, from the smallest single property infestations to those operations that target an entire city.

The fact that a particular property or site is infested with rodents may or may not be known to those who live in or own the property, but at least the property is likely to be owned by somebody, and it is therefore in the owner's potential interests to know whether an infestation exists and, if it does, to do something about it. On a larger scale, such ownership of infestation does not occur and so it is not in any one person's particular interest to try to identify the patterns of activity on a larger scale. Who 'owns' the problem of a rat or mouse that is travelling between a number of properties? Ownership of an infestation implies responsibility for doing something about it, and doing something about it has cost implications, so it may be sometimes be perceived to be better not to 'own' the problem!

Estimating levels of rodent infestation

The design, development and practical implementation of surveys should be based upon the objectives of the survey. There is little point in spending time and resources in undertaking a statistically robust survey if the data do not require to be robust. Alternatively, if scientific validity is required, then the survey and data collection procedures used must provide the level of reliability required. A very useful guide to the design of rodent surveys (*Integrated Pest Management: Conducting Urban Rodent Surveys*) has been produced by the US Centers for Disease Control and Prevention (CDC, 2006).

There have been many attempts to try to identify levels and distribution of infestations over the years. Most of these have been undertaken by national governments and city or town municipalities as a part of their responsibilities under environmental health legislation. Other surveys have been undertaken as parts of research activities by laboratories or rodenticide manufacturers. One of the earlier scientifically rigorous attempts to quantify the extent of rodent infestation in an urban area was undertaken in the south coastal town of Folkestone in England (Drummond *et al.*, 1972, 1977). Here, successful attempts to reduce the levels of Norway rat (*Rattus norvegicus*) infestation over a number of years necessitated the early identification of the levels of the infestation at the start of the project. Structured surveys, undertaken over the length of the project, enabled monitoring of the progress of the control programme.

Subsequently, an extensive randomized survey was undertaken in London in 1972 (Rennison and Shenker, 1976), which was designed to identify levels of commensal rodent infestation in domestic and business premises. This randomized survey proved so successful that it was extended to all of the Local Authorities in England and Wales (Rennison and Drummond, 1981). These extended surveys were designed to provide data not only on infestation levels, but also on who was undertaking the control and what techniques were being used. The annual completion of these surveys over a number of years also enabled changes in infestation levels and other trends to be reliably identified. These annual surveys stopped in 1979, but a repeat random survey was undertaken in 1993 using identical stratification and selection procedures so that the data collected would be comparable to that collected in the 1970s (Meyer *et al.*, 1995). A further randomized survey was undertaken in 1996 (Langton *et al*., 2001) as part of the English House Condition Survey; although the survey was randomized, the techniques used were not the same as those in earlier surveys and the data are not strictly comparable. In this later survey, the presence or absence of rodent infestation could be correlated with housing conditions.

Other surveys have been undertaken that were designed specifically to identify and eliminate infestations or foci of infestation. These are not based upon the inspection of randomized premises, but upon surveys in targeted premises and upon reports of activity from members of the public. While less statistically robust than randomized surveys, such surveys can provide excellent data on the distribution of rodent activity and the success of control operations over time. The resources that might have been used to undertake the more time-consuming randomized surveys are used instead to control the rodents. The most thorough and long standing of these surveys was probably that undertaken in Budapest in Hungary (Bajomi *et al*., 1996), starting in 1971 and continuing for 23 years. This survey was, again, like the Folkestone survey in the UK project, undertaken as a part of a control programme. The survey was thorough and was designed first to identify the initial levels of Norway rat activity so that the efficacy of the control programme could be assessed, but also to identify the distribution patterns of these rats so that control and environmental management resources could be effectively targeted.

Another long-standing data collection programme is that undertaken by the National Pest Technicians Association (NPTA, 2001–2011) in the UK. In this, the NPTA collates annually the numbers of complaints from members of the public on Norway rat and house mouse activity received by the pest-control departments in Local Authorities from within the UK. The collection of these data has now been undertaken since 1999, and while not statistically robust, it does provide a picture of the trends in public complaints over this period, in the absence of other more robust data. Smaller-scale surveys have been undertaken to assist in the identification of the severity and distribution of a problem prior to the implementation of a control programme (Meyer, 1978).

Alternatively, a survey might be designed to identify not only where and with what frequency rodents might be present, but also to try to identify which environmental factor might be leading to their presence. In one instance, a survey was designed to identify what structural characteristics of dwellings determined the distribution of house mouse infestations in Manchester, UK (Murphy *et al*., 2003). In another survey undertaken in Laos (Promkerd *et al*., 2008), the distribution of roof rat (*Rattus rattus*) and Polynesian or Pacific rat (*Rattus exulans*) activity, and the potential environmental factors that determined this activity, were identified through a structured survey. In a survey undertaken in Sierra Leone, housing quality was shown to be related to the distribution of rodents and to risks from Lassa fever (Bonner *et al*., 2007).

A number of large-scale urban rodent-control programmes have already been mentioned. There are many others from many parts of the world. For example, in New York State in the USA, rodent infestations were decreased by 84% (Brooks, 1974), and a large-scale programme in New York City significantly reduced infestations (Raphael, 1970). In Rio de Janeiro, a reduction of rodents of 80% has been claimed within 2 years (Moojen, 1981). All of these are examples of wide-scale, municipally organized rodent-control programmes whose success was dependent upon a number of factors, including good data on the distribution and levels of rodent infestations.

Municipal and householder rodent-control strategies essentially follow the principles described in Chapter 5 under 'Case Study: Food Stores'. The development and progression of a rodent-control strategy will always depend upon access to sound survey data.

Integrated Pest Management (IPM)

Integrated pest management, or in this case, integrated rodent management, is a term widely used to describe the incorporation of all the elements of an effective rodent-control programme into a single, coherent strategy. IPM means different things to different people, but essentially incorporates the following elements:

- clear identification of the nature of the infestation and the objectives of the programme;
- control operations undertaken by trained and qualified staff;
- use of appropriate chemical control measures applied safely;
- use of appropriate physical control measures applied safely;
- use of effective environmental management techniques;
- introduction of effective record keeping and monitoring; and
- regular review of the progress of the programme.

Any rodent-control programme will need to include all of these elements if it is to be effective.

Best Practice and Audit Schemes

In many ways, not a great deal has changed in rodent control since the first edition of this book 20 years ago. We still use broadly the same rodenticides, formulated and applied in much the same way.

One area where there have been significant changes has been in the field of third-party auditing of pest-control programmes, particularly in the food industry. The increasing need for and pressure on the food industry to produce food for human consumption that meets standards of quality and safety has resulted in many pressures on food producers to maintain and to demonstrate that their pest-control programmes are fit for purpose. These programmes must demonstrably deliver pest-free environments in which the food being produced cannot be contaminated by such items as dead rodents or pieces of dead rodent, rodent droppings or hair, and that not only the food but also the packaging is free of contamination by rodents.

As a means of achieving this, a number of organizations around the world have set standards, including standards relating to rodent control, that have to be met by food producers, and the producers are audited to these standards. Increasingly, customers will not purchase from these producers if they do not demonstrably meet these standards through holding certificates that demonstrate that they do so (Felix and Kupfer, 1988).

Perhaps the organization with the most international reach is AIB International, which is based in the US, and is committed to ‘protecting the safety of the global food chain’. AIB International has consolidated standards for a range of business types, including Agricultural Crops, Beverage Facilities, Dairy Facilities, Food Packaging Facilities, Food Distribution Centres, Fresh Cut Produce, Grain Handling and Retail Facilities. Other organizations that provide similar standards and auditing programmes include the British Retail Consortium and many supermarket chains, such as Wallmart, Marks and Spencer, Tesco and Sainsbury’s and, for the farming industry, Red Tractor. Essentially, all these organizations set similar standards as far as rodents and rodent-control strategies are concerned. Auditors will check for evidence that:

- There is a rodent-control programme in place at the facility.
- The staff involved are appropriately qualified.
- There are no rodent infestations present.
- A comprehensive monitoring programme is in place.
- Monitoring data are collected and analysed.
- Appropriate rodent control is applied when necessary.
- Risks from rodents and control measures are minimized.
- The overall strategy is reviewed regularly.

The international nature of these standards reflects the international nature of the food supply and distribution industry as well as the international nature of rodent infestation issues.

Food Processing and Production Units

Food processing and production units and livestock units are considered together for the purposes of this chapter because they have one essential component in common: the availability of very significant quantities of food (by definition) in one place or over a relatively small area. They often also provide an abundance of water within this area and a structural environment that is more often than not attractive to rodents and provides the shelter that they require to survive. Thus, these units have in common the fact that they provide the three essential components that enable rodents to survive and often thrive: food, water and harbourage. The range of typical environments covered by this definition will include such places as:

- postharvest commodity stores (grain stores, food clamps, etc.);
- food processing units (food factories, bakeries, etc.);
- food warehousing;
- food distribution and transport systems (containers, trailers);
- retail outlets (shops, markets and supermarkets);
- restaurants and commercial kitchens (hospitals, schools, etc.);
- livestock feed stores; and
- livestock production units (pig, poultry, cattle units, etc.).

A useful summary of some of the issues associated with rodent control in food storage environments, particularly in developing countries, is contained in the *Food Storage Manual* from the UK's Natural Resources Institute and the World Food Programme (Walker and Farrell, 2003).

In addition to all the normal reasons why rodent control is important in the food chain, there are far-reaching consequences of rodent contamination of a processed food that subsequently enters the human food chain. Such an event can generate a customer complaint, the consequences of which can be significant and include the following potential costs:

- legal costs of defending a prosecution;
- fines for contraventions of legislation;
- loss of customer revenues due to bad publicity;
- damage to the 'Brand'; and
- costs of recall of potentially damaged product.

The contamination of a high-profile international brand of food and the attendant publicity can cost millions of dollars in lost sales, recall and rebranding costs. In one case known to the author, the loss of an important customer as a result of rodent contamination of product resulted in the closure of the business and some 70 staff redundancies, and a compensation claim (paid by the insurance company) of £500,000.

The standards required of these units may be set either by national or local government legislation, in which case the units are usually audited by local environmental health personnel. In addition, standards are set by the customers who audit the facilities themselves or by third-party organizations that set their own standards and audit on behalf of customers (see previous section). Failure to meet standards set by local and national government legislation can result in closure or significant fines, and failure to meet the standards set by auditors can result in loss of customers or the removal, even temporarily, of a customer's business.

Rodent control in food units can be undertaken either by the staff at the food unit itself or by professional contractors providing a service of pest (rodent) control. The majority of facilities will use the services of a professional pest-control company because the standards that they have to meet require high levels of technical competence, which are not so easily achieved under home-managed operations.

Domestic/Household and Small Business Control Options

Domestic, householder and business operators may seek to manage rodent problems because of potential disease threat, damage (or threat of damage) or aesthetics, or for all of these reasons. For most smaller rodent infestation situations, and in most countries, some option exists to 'do it yourself' (DIY). A larger percentage of less affluent members of a population may favour these methods, because they cannot afford professional pest-control services. Regulations governing householder control materials and methods are frequently written to preclude the use of the more hazardous chemical rodenticides and to restrict the placement of rodenticides to the areas that are least likely to result in non-target hazard and contamination of food or the environment.

Whether or not householders attempt their own rodent control may be based on cultural, social, religious or economic reasons. When a tradition of DIY pest control exists, either in a locality or with a single family or group, then there may be a tendency for further control to be applied when needed (though perhaps not with the most appropriate or efficacious techniques). Such efforts may be limited to chemical control rather than possible (but often neglected) environmental management techniques (sanitation, proofing, etc.). Alternatively, efforts may wrongly concentrate upon structural pest control without regard to surrounding crops or vegetated areas that can harbour rodents. These adjacent areas, if untreated, may leave a ready source for reinvasion of villages and towns when seasonal effects or crop harvests reduce food or harbourage. Although integrated programmes involving professionals can deal with area-wide control, a principal limitation of DIY efforts is that such isolated efforts do nothing to reduce rodent infestations in the adjacent premises or in the neighbourhood, and are restricted to the land and property owned or under the control of the individual doing the pest control. These individuals have no legal responsibility, nor do they necessarily feel any sense of responsibility, for the larger environment.

Among more wealthy householders, or where a professional or municipal extermination service is available, there may be less of a tendency to apply DIY measures by the householders themselves. A reluctance to seek outside help with rodent control may stem from a fear of publicizing one's pest problems. Other cultures or beliefs may consider the suffering or death of pest rodents objectionable, due to religious or philosophical (e.g. animal welfare groups) tenets. In many areas and cultures, admission of rodent problems may be considered as a sign of poor housekeeping. However, even good housekeeping may have little effect upon rodent infestations if the neighbourhood harbours a ready supply of invaders, structures that are open to rodent movements, and foodstuffs that are not maintained in rodent-proof containers.

More than 50% of homeowners in the USA try the DIY method of pest control (NPCA, 1986). In England and Wales (Meyer *et al.*, 1995), the percentage is less than this, at about 25%, although the figures vary with the species being controlled and the areas concerned. Householders are more likely to control house mice than they are Norway rats. Those in village and rural areas are also more likely to undertake their own control than those in urban and semi-urban areas. In England and Wales, some 25% of infested premises experience no control from any source. This may be due either to a lack of awareness of the problems that rodent infestations can cause or to an increased sympathy for the rodents themselves and a reluctance to kill them. There appears to have been a consistent increase in levels of Norway rat infestation in domestic premises over the last 30 years, though the reasons for this are not clear and are probably complex (Meyer *et al.*, 1995; NPTA, 2001–2011).

There is evidence in England and Wales that rodent infestations in domestic premises are closely linked to a range of factors relating to housing quality and the adjacent environment, and to such factors as the presence of pets/livestock (Langton *et al.*, 2001). Domestic premises with pets or other livestock have infestation levels some two to four times higher than those without. These data relate to animals such as rabbits, chickens and caged birds that are permanently housed in the garden or outdoor area, as opposed to companion animals such as cats and dogs that may spend some time in the garden but live inside the house. The data are also confounded with a variety of other factors, including housing density and environmental quality.

Simple rodent traps and rodent-proofing materials are available to private householders from a number of sources, normally without restriction. These are often referred to as 'retail', 'over-the-counter' (OTC), or 'consumer' rodent-control products. More complex traps or repellent (electromagnetic or ultrasonic) devices may be only available from a vendor (or mail-order company) specializing in pest-control materials. Access to supplies over the Internet will have increased householder use of a wider range of rodent-control products in recent years. The more common chemical rodenticides, such as those with the lowest hazard, general-use labels, are usually available on the open market, such as at garden shops or local DIY outlets. In some countries, a simple written log is kept of persons buying all economic poisons, including rodenticides. This serves as a source of useful information to authorities, especially in cases of intentional product misuse. Such sales are usually restricted to adults, and occasionally limited to local landowners.

The growing popularity in Europe, the USA and elsewhere of non-chemical control methods reflects an increasing public awareness of environmental and humaneness concerns. Environmental activists and vendors of pest-control materials that 'go green' are quick to recommend or prefer non-toxic approaches such as traps (including glue boards) or repellents. Yet these tools are limited in their efficacy (see Chapter 5). Traps still require that the dead or dying rodent caught be disposed of. This is a vexing and stressful job for many individuals whose only regular contact with non-human animals may be with pets, rather than pests. In areas where traps are considered inexpensive, they may be discarded with the captured rodent after a single use. Repellents may displace rodents only from specific areas and only for a limited duration, unless the underlying conditions supporting the infestation are removed. Glue boards, while non-chemical, may be criticized on humaneness grounds (Frantz and Padula, 1983), even though in some countries, the UK for instance, Codes of Practice for the use of glue boards have been produced in an attempt to ensure that they are used as effectively and humanely as possible (Pest Management Alliance, 2010). In other countries, Ireland for instance, the use of glue boards is illegal.

Finally, householders tend to purchase very limited quantities of rodent-control materials, such as a few traps, or one or two boxes of rodenticidal bait. Without the specialist knowledge of rodent control, there is often little appreciation of how much or how many control materials are required or for how long they should be used and where. The limited amount purchased is often inadequate to do the job, because of the larger than anticipated home range of pest rodents and the need to apply control materials at several points throughout infested areas over an extended time period.

Trapping efforts to control rodents may be more common in areas where less of a premium is put upon the personal time required to place and service such traps, or where aesthetics do not preclude ready handling and disposal of rodent carcasses. In some countries, servicing traps may be the province of women or children, at least after placement. Elsewhere, the traps themselves may be too valuable or too prone to theft or vandalism to delegate the trapping effort beyond an adult user, and only protected indoor placements may be made. Release of live-caught rodents may be made outside the structure in nearby areas, so relocating but not necessarily eliminating the problem. The use of traps has been shown to be effective in reducing the numbers of rodents, and damage and losses due to rodents. To achieve such results, though, the traps must be used intensively and the trapping must be used intelligently (Belmain *et al.*, 2003).

The use of poison baits by householders is well documented in terms of what is purchased, but little evidence is available on how correctly or safely such materials are actually used. That such products do work in killing rodents is not disputed based on market surveys and the limited number of complaints that manufacturers normally receive on popular brands. For example, a survey indicated that from half to two-thirds of DIY users of retail products such as rodenticides, traps and glue boards were very satisfied with the results (ICI Americas, 1986). However, there are frequently some government or consumer-safety advocate concerns that labels and instructional materials may not be adequately reviewed and understood, or that such products are posing an unnecessary risk to non-target organisms from inadequate or improper placement.

Beginning in 1983, after analyses of data concerning human exposure to rodenticides, the US Environmental Protection Agency (EPA) promulgated additional guidelines recommending the use of tamper-proof (or at least tamper-resistant) bait stations in areas accessible to children and non-target animals (Jacobs, 1990). Incidents of misuse or exposure appeared greater with OTC rodenticides used by householders, farmers and others than for rodent-control materials applied by professional pest-control operators (PCOs) or municipal authorities (Trammel and Buck, 1990). The use of such tamper-resistant bait containers has now been adopted universally, certainly by professional pest controllers. Their use by householders and amateurs is probably not so universally adopted owing to the costs involved. Furthermore, the use of tamper-resistant bait containers is likely to have an impact on pest behaviour and these are not so readily used by species that may have a tendency to be neophobic, such as the Norway rat. In cases like this, the use of tamper-resistant containers may interfere with the progress of the pest-control treatment.

Professional Pest-Control Operators

Most countries have pest-control specialists for hire who control rodents, and often other pests. Depending on local laws and practices, these professional PCOs may conduct rodent control in residential areas, in commercial (business) areas, or in both. A nationwide survey indicated that about 30% of residential households in the USA had used a PCO service within the past year, and that two-thirds of PCO users occurred in the warmer and more humid south-eastern region of the USA, which is subject to greater rodent and insect pest pressures (ICI Americas, 1986). Whereas many businesses contract with pest-control companies to meet their rodent-control needs, it is not uncommon for some businesses to perform their own in-house pest-control operations, which replace or supplement PCO services.

Contracts are commonly written with business owners stipulating the level of control and interval of inspection – normally monthly, but sometimes weekly or even more often on demanding accounts. Residential treatments may be limited to two or three visits: one to survey, one to set out bait, and one to pick up bait and other equipment. A yearly inspection of the premise might be instituted to see if the problems had reoccurred. Some sort of warranty or ‘guarantee’ may be offered for a specified period that will cover free retreatments if problems reoccur. Pest-control companies are normally insured to provide coverage in the event of accidents or liability actions.

Rodent control accounts for approximately 20% of the total professional pest-control market in the USA, with 57% of this rodent work done for commercial or industrial accounts, and the remainder for residential accounts (Mix, 1986). House mice (*Mus musculus*) in the USA account for 58% of the rodent-control business, compared with 24% for Norway rats and 13% for roof rats (Mix, 1986). Because of liability concerns and generalized worries about exposure to chemicals, many PCOs favour the use of physical control techniques inside homes where children or pets are present. PCOs also use proprietary ready-to-use baits (see Fig. 11.1) and they may be required to provide literature to their customers describing the toxicants used, and giving toxicological and hazard information, including product labels and material safety data sheets.

Pest-control technicians around the world tend to use their trade-association publications as a primary source of new information. In addition, publications from

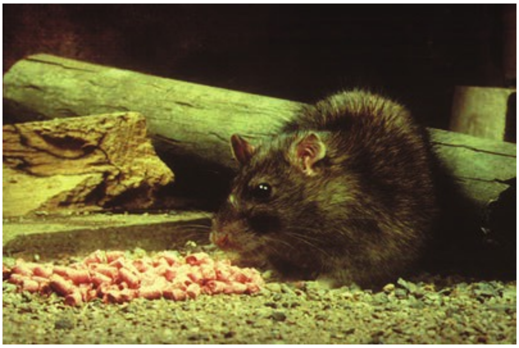

Fig. 11.1. The Norway rat (*Rattus norvegicus*) consumes a proprietary, pelletized rodenticide bait. Such ready-to-use baits are favoured by pest-control operators because of their convenience. The attractiveness of the baits is an important determinant of treatment efficacy, and is influenced by many factors including, among others, the texture, smell and intrinsic palatability of the bait, where it is placed by the pest-control practitioner and the prior experience of the target infestation. Best practice now dictates that such baits should be put out in bait trays and, where access to the bait by non-target species cannot be prevented by other means, in tamper-resistant bait stations.

suppliers and, in some countries, independent publications provide additional and very valuable sources of information. In Europe, a best practice advice for professional pest-control technicians has recently been provided by the European Chemical Industry Council (Cefic, 2013). About 20% of companies in the USA belong to the National Pest Control Association (NPCA). The NPCA in the USA and the British Pest Control Association (BPCA) in the UK offer technical assistance. Throughout the rest of Europe, similar trade associations support their members in the same way through regular conventions, training programmes and technical material, and provide pest-control companies with an awareness of, and a larger voice in, the areas of government regulations, public perceptions of the use of pesticides and other industry-related issues. On a collective basis, there are federations such as FAOPMA (Federation of Asian and Oceania Pest Managers Association) and CEPA (Confederation of European Pest Management Associations).

Pest-control consultants are increasingly available to offer advice, whether relating to an occasional need, or as part of a regular retainer and review of a company's ongoing operations (Milgate, 1986). Computer databases (e.g. the National Pesticide Information Retrieval System in the USA) and services are also available and may be used by larger companies or technical specialists to access current research and publications across the many disciplines of relevance to rodent control. Other information sources are local distributors of pest-control products, product manufacturers, university agricultural extension or wildlife biology departments, and pest-control handbooks and reference works (for example, the *British Pest Management Manual*, the latest version of which was produced in 2012, see Allan and Meyer, 2012; and the (American) *Handbook of Pest Control*, see Mallis, 2011). The proceedings of the Vertebrate Pest Conferences from the University of California (see http://www.vpconference.org/Proceedings_of_the_Vertebrate_Pest_Conference/) are also a valuable source of information.

Most pest-control operators recognize the concept of IPM, in which the application of rodent-killing materials is only one part of reducing rodent infestations. Sanitation and rodent proofing are also recognized as important elements to reduce the carrying capacity of the environment to maintain pest rodents (particularly for rats, because mice need little in the way of food or entry ways to cause an infestation). Yet PCOs often cannot greatly effect improved sanitation or rodent-proofing measures due to the isolated nature of the infestations they are treating, and the inability or inappropriateness to motivate their customers to make the necessary changes. Some pest-control operators undertake rodent proofing as an additional service and source of revenue, and in some areas, pest-control companies are hired to conduct rodent control by municipalities on an area-wide basis. Bajomi and Sasvari (1986) illustrate a large and continuous programme in Hungary, and Colvin *et al*. (1990, 1992) describe PCO involvement in a sizable highway-construction project in Boston, Massachusetts.

Municipal Authorities

In most countries, the government authority for laws and regulations or enforcement concerning rodent control lies either with an arm of the national public health service or equivalent, or with the national departments of agriculture (or animal production), the environment, or a combination of these. In some cases, various national, regional and local municipal government agencies may all have administrative responsibilities for rodent control, such as when the location of the infestation is considered part of their responsibility.

Municipal authorities will generally conduct rodent control in government and public buildings, and in government-subsidized housing. Rodent control in parks and public areas near housing may also be needed. Claffey *et al*. (1986) give a useful summary of an integrated programme to control rodents along a popular waterfront park area in California. In addition, many communities provide some rodent-control services to its citizens, including instructional literature, free bait or loan of traps, or even extending to actual control efforts. Other countries, such as the UK, may provide rodent-control services that extend beyond municipalities to farm situations. Pest control in the UK used to be considered a public service, funded by local taxes or charged at cost, and performed by employees of the local town council. Although this position still persists, there is an increasing requirement that costs are recovered from customers and, increasingly, charges are made for rodent control.

Where towns and villages are contiguous with crop fields, orchards, forests or other potential rodent habitat, and these different habitats share the same rodent species, integrated pest-control efforts by cooperating agencies can most effectively control rodents by attending to rodent levels and movements in both agricultural and nearby inhabited areas (for example, see Richards and Buckle, 1986). For examples of national, sustained integrated rodent-control programmes, see Ku (1986) (Taiwan) and Al Sanei *et al*. (1986) (Kuwait).

Municipal authorities have an advantage over contracted pest-control services in that such authorities can order, supervise or participate directly in efforts to improve sanitation and rodent proofing, through their periodic or regular campaigns in the community. Among such authorities, rodent killing is usually only one aspect of reducing rodent infestation rates in a locality, and such organizations have professionals in many disciplines, such as refuse collection, street and sewer maintenance, building inspection, food and restaurant inspection, health aids, etc. It is the coordination of these professionals that can change the overall characteristics of a community for the better, and reduce the carrying capacity for rodent infestations, while also improving the general health and well-being of the inhabitants. In addition, municipal authorities and the effective regulations that they promulgate can ensure that architects and engineers consider changes in the design and construction of structures to reduce or eliminate many rodent problems through the use of methods and materials to reduce or eliminate rodent entryways or harbourage.

Proper organization of community or area-wide rodent control is essential. Groups or agencies responsible for all facets of rodent control must recognize and accept their roles and work together in a coordinated way towards a common goal. Drummond (1985) gives a useful overview and summary of urban rodent-control programmes. A useful checklist of important conditions or factors to consider in organizing rodent control is given by Howard (1984). A comprehensive urban rodent-control programme may include the following elements: surveillance, environmental sanitation, community education, code enforcement, rodent control, and the evaluation of prevention and control activities (Anonymous, 1980).

Surveillance should be conducted by trained personnel according to established procedures, resulting in written records of observations that allow rodent signs and conditions fostering infestations to be quantified. Areas with a history of problems, with dense human populations, or of known prior endemic disease, should be surveyed more regularly and intensely. Determining rodent parasite or microbiological load, or disease antibody titre, may be a necessary part of public-health monitoring where rodent-borne diseases are known or suspected. For example, Thierman (1977) established that over 95% of Detroit (Michigan, USA) inner-city Norway rats were carriers of *Leptospira* organisms. The required sanitation efforts can be coordinated with control activities. In addition to ensuring regular refuse collection, rodent-control campaigns can usefully be preceded by an annual or semi-annual programme of collection of additional refuse and debris, or by programmes of cleaning areas or doing rodent proofing.

Community educational activities can include presentations on rodent biology, behaviour, public health importance, damage and control methods. These presentations can be given to civic groups or block associations, and to schools or professional groups, and handouts, posters and other materials disseminated. Fairs, parades, seminars, news, radio and television releases, contests and other approaches have all been successfully used to educate the public about the need for rodent control. A survey conducted to evaluate a multimedia campaign publicizing an area-wide rodent-control programme in Kuwait found that films were ranked the most popular vehicles (32.4%), followed by advertisements (23%) and posters (16.8%) (Abdul Sanei *et al.*, 1986).

Proper environmental management is important to the success of rodent control. Many communities have laws governing the proper maintenance of garbage, refuse and harbourage. Municipal authorities often have legal authority to give citations to individuals found violating local ordinances. The posting of conspicuous signs notifying the community of an offending individual is another method of achieving results.

In the USA, no one branch of local, state or national government is responsible for urban rodent control. The US CDC in Atlanta, Georgia, has been most commonly involved through recognition of the threat to public health that these pests represent. Funds to over 100 US communities were administered by the CDC under the Federal Rat Control Program between 1969 and 1984 (some of this under the organizations that preceded the current CDC – the Center for Disease Control and the National Communicable Disease Center). This programme was stimulated, in part, by the discovery of warfarin resistance in the USA (Jackson and Kaukeinen, 1972). Programme cities were surveyed by federal authorities and ‘target areas’ of the greatest need established. The incidence of rodent signs, unapproved refuse and garbage was recorded before and after treatment. Municipal rodent-control workers were often recruited from the community and, in fact, the hiring of minority residents was a required aspect of federal funding. This created strong local ties and some upward mobility for some residents, but these positions were seldom well paying or considered particularly desirable, and with the loss of federal funding, such individuals were usually lost. Municipal programmes can be more successful if rodent-control staff have a professional image and a position with competitive salaries and benefits (Howard, 1984).

During the US national programme, blocks of residences showing signs, food and harbourage levels below established minimums were declared ‘maintenance blocks’ subject to annual or semi-annual surveillance and treatment, whereas intensive control efforts moved to more highly infested areas. Although harder to determine and to quantify, surveys may also usefully note the use pattern of the site by people, pets, domestic animals or wildlife, as well as the attitudes of residents or persons present on the site, the potential for vandalism or unsafe aspects of treatment, and the history of rodent problems and prior control.

As the US national rat control effort wound down in 1984, after the expenditure of some US$360 million, dozens of US municipalities had effectively reduced their worst 'inner-city' rodent problems, and some 8 million persons had benefited (Jackson, 1984). Local municipal agencies were expected to assume the maintenance of these areas and to further control less infested urban areas with state and local funding. For many cities, the transition from federal funding led to the downscaling of staff and programmes. The educational component that was the most critical in changing public attitudes and practices was usually the first to be discontinued with budget cuts. Interestingly, the national programme was initiated by Congress over political concerns involving rat problems, notwithstanding the greater problem that mice represent throughout much of the USA (and leaving mice for commercial operators to control?). Further, while studies in the USA (e.g. Barbehenn, 1970) have found sewer rats to be prevalent and disease carrying, little organized sewer rat control has been attempted, except in a few larger metropolitan areas of the USA. There is perhaps greater attention to sewer rat control as a specific programme in Europe and Britain (for example, see Forbes, 1990).

Continued urban budget restrictions have limited many urban rodent-control operations to that of a 'complaint-basis' service. Such activities alone may tax a sizeable staff; for example, the city of Los Angeles and its immediate surroundings generates over 40,000 rodent complaints yearly, comprising 40% house mice, 30% roof rats and 30% Norway rats in the inner-city areas; in the suburbs, over 90% of complaints deal with roof rats as a result of increased landscaping providing harbourage (R. Baker, personal communication).

Orange County, California, has an urban roof-rat control programme, which is described by Challet (1986). The Orange Co. vector control district has 16 technicians who have rat, fly, mosquito and midge responsibilities. In 1985, they answered 7281 complaints on rats, and they visit about 41,000 properties for inspection and treatment yearly. The complaint/response programme in Orange Co. is considered more cost-effective than neighbourhood surveys. Upon a call for assistance, an appointment is made within 2 days to visit the property, where the service technician checks for rodent signs, harbourage, food sources and entrances into the structure. Control inside the building is the responsibility of the owner or a pest-control operator, and the municipal representative does not inspect there. The technician gives written recommendations and educational materials to the owner. If baiting is needed, the owner must first sign a release from liability. Adjacent property is then surveyed and similarly treated, if necessary, as infestations rarely respect property boundaries. Treated areas are revisited within 3–6 months.

This pattern of response is common in many US cities. Nevertheless, it is believed that some cities are in equal or worse condition in terms of inner-city rodent infestations than they were before 1974 (Pratt, 1991). Growing regulations, liability concerns and the need for municipal authorities to be certified has resulted in increasing reliance on pest-control operators by municipal authorities to conduct various services under contract. In other countries, such as Germany, municipal health authorities with enforcement or referral capabilities do not exist, and pest-control operators must deal directly with political representatives of municipalities and advisory groups who may be opposed to the use of chemical control agents (Peck, 1992). Furthermore, with the lack of pest-control efforts by municipalities as a public service, householders in Germany must pay private PCOs (Peck, 1992).

Municipal authority rodent-control efforts also should be preventive in nature, reducing the chance that a rodent population outbreak, sudden availability of stored grain, etc., could result in a sustained rodent problem. Yet, even at their best, area-wide rodent-control efforts rarely completely eliminate the rodent problem, because they cannot completely rid treated areas of conditions that foster rodent populations. Intensive and sustained efforts can result in 'rat-free' towns, as demonstrated in Germany by private contractors (for example, see Telle, 1974; Becker, 1983), and by the rat-free provinces in Canada (Dorrance, 1984); but note that these authors generally equate infestation rates of 0.5% or less as 'rat-free'. Such examples are, however, few, and it appears that the resources and circumstances for successes like them – for example, the required level of sanitation, rodent proofing, and intensive monitoring and the application of control materials – are rarely present.

Future Options and Conclusions

There are many issues both locally and globally that make the future look bleak and far from promising for those involved with and committed to effective rodent-control programmes. Growing world human populations are increasingly restricted to urban built environments and these increasingly provide ever more ideal environments for commensal rodents, which, as their name implies, are particularly well adapted to living in these environments. The enormous populations predicted for many cities and the smaller increases predicted for most are difficult to service effectively. Hence, there is a tendency for the environments to deteriorate, for poorer quality housing, for less effective waste-disposal systems, for poor-quality sewer systems and for populations that might be increasingly alienated, all of which produce environments that are ideal for commensal rodents, so we can expect these populations to increase.

The range of effective techniques that are available to those undertaking rodent control is reducing rapidly. The amalgamation of manufacturers producing rodenticides inevitably reduces the range of formulations available to users as the remaining manufacturers restrict their ranges to those that produce the best returns. The move away from the supply of concentrates to users as a part of a safety strategy reduces the flexibility involved in being able to mix formulations to suit a particular population of rodent or a particular environment. The increasing restriction to ready-to-use rodenticides that are perceived as non-spillable, for safety reasons, means that baits supplied may be easy to handle and to manage, but they may not always be as palatable as the less easy to use and manage loose grain baits.

Governments are increasingly involved with restricting and managing access to pesticides, including the access to rodenticides. This involvement is costly to manufacturers and often results in increasing restrictions on how and where rodenticides can be used. The costs of these procedures mitigates against manufacturers supplying what might be very effective rodenticides, simply on the grounds that they are too costly to register.

The most effective rodenticides continue to be those based on anticoagulants, but these have now been used for 60 years. There is increasing evidence that the continuing selective pressure from the continued use of these anticoagulants is selecting rodent populations that are increasingly resistant to the anticoagulants; this selective pressure shows no sign of reducing over the coming decade(s) and resistance management will become an increasingly important issue over that period. In addition, the evidence that genetically based behavioural resistance is being found in some areas gives cause for concern.

Good and effective rodent control is time-consuming and, therefore, expensive. Those involved with food production and rodent control in businesses will continue to have to afford the costs of these operations because they have no choice, although there is evidence that they are looking for increasingly less expensive contracts as financial situations tighten. Moreover, these increasing costs cannot be met so easily by central governments and municipalities, and it is likely that over the coming years the resources committed to effective and proactive rodent-control programmes will reduce. Private householders will be restricted in a similar way by the costs associated with using pest-control contractors. There will be a trend to more DIY control by amateurs, and the rodent infestations will be less effectively controlled.

Public attitudes to rodents are changing; people do not always understand the potential threat posed by rodents, and rodents are increasingly seen by some as a natural part of the environment and so infestations not so frequently controlled. Similarly, there is an increasing move away from using what might be seen as dangerous and 'nasty and inhumane' rodenticides towards the use of physical methods of control, which are less effective and not necessarily more humane. The need for effective, well-managed and planned rodent-control programmes is likely to increase in future years. Unfortunately, they are likely to be more difficult to achieve as financial and technical constraints become more limiting.

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12 Rodent Control in Practice: Temperate Field Crops and Forestry

A.P. Buckle[1] and H.-J. Pelz[2]
[1]*School of Biological Sciences, University of Reading, Reading, UK;*
[2]*Vertebrate Research Group, Julius Kühn-Institut – Federal Research Centre for Cultivated Plants, Münster, Germany*

Introduction

Agriculture in temperate latitudes is extremely diverse. Cropping systems are sometimes based on a single, major component but more often comprise a mosaic of different elements. These elements include the farming of arable crops, such as wheat, barley and maize, the use of pasture and rangeland for the production of wool, milk and meat, the cultivation of semi-permanent top-fruit tree crops (tree fruits), a wide variety of vegetable and fruit crops, including those grown for fodder, oil, sugar and energy production, and the planting of forest trees for timber and wood pulp. Without exception, agricultural production in all of these systems is adversely affected by rodent pests.

The species that are pests in temperate commensal situations belong almost exclusively to the family Muridae of the order Rodentia. Their cousins of the families Cricetidae and Sciuridae come into their own, though, as pests of temperate agriculture. The impact of these animals on agricultural activities is reviewed elsewhere (Chapter 3).

The purpose of this chapter is to give more detailed consideration to some of the most important of these rodent problems and to describe the control strategies developed to combat them. These strategies are as varied as the nature of the problems they seek to solve. Rodenticides (Chapter 6) feature prominently, but a very wide range of other techniques is used as well, including trapping, shooting, habitat manipulation, the planting of rodent-resistant varieties, and the use of chemical repellents and physical barriers (Chapter 5).

Arvicoline Voles as Pests in Agriculture and Forestry

Distribution and nature of the problem

Some species of arvicoline voles (Arvicolinae, Cricetidae) are serious pests of agriculture and forestry across the Holarctic. Voles tend to show fluctuations in abundance, with devastating outbreaks, particularly in areas that are homogeneously cultivated on a large scale (Frank, 1957; Delattre *et al.*, 1999, 2009). The most pronounced multi-annual population cycles can be observed in northern Fennoscandia at latitudes above 60°N, with peak densities between 100 and 400 individuals ha^{-1} (Krebs, 2013). However, at latitudes between 40°N and 60°N, population density oscillations can be even greater, resulting in peak numbers of several thousand individuals ha^{-1} in specific European regions and years and it is these that cause the heaviest damage to farm and forest production (Jacob and Tkadlec, 2010). Population peaks of the smaller *Microtus* species are separated by between 2 and 5 years (average 3), while *Arvicola* population peaks occur every 5–8 years (average 6) (Saucy, 1988; Krebs, 2013), often with spatial synchronization across large areas.

Vole cycles have been studied extensively with the intention of forecasting their periodicity and their determinants so that control measures can be initiated to minimize their impact (Habert, 1988; Wieland and Sellmann, 1995; Davis *et al.*, 2004; Jacob *et al.*, 2010; Sullivan and Sullivan, 2010). In future, such analysis of local population kinetics and impact factors will make it possible to anticipate outbreaks and organize timely preventive action.

The driving force behind population cycles has been a matter of discussion among scientists for many years (e.g. Stenseth, 1985; Krebs, 1996, 2013; Korpimäki *et al.*, 2004; Lambin *et al.*, 2006). There is evidence that cycles in northern latitudes are mostly driven by specialist predators like the least weasel, *Mustela nivalis*, and food limitation (Turchin and Hanski, 2001; Klemola *et al.*, 2003; Korpimäki *et al.*, 2004), while in more temperate latitudes generalist predators and additional factors such as weather conditions or landscape ecology seem to gain in importance (Hansson, 1999).

From an economic perspective, three genera of voles are most relevant due to their population cycles and periodical outbreaks: *Microtus*, *Arvicola* and *Myodes* (previously *Clethrionomys*).

Microtus

In North America, ten different species of the genus *Microtus* have been implicated in damaging outbreaks in orchards and forestry but, of these, *M. pennsylvanicus*, *M. pinetorum* and *M. montanus* are the most important (Godfrey and Askham, 1988). In no-till agricultural crop fields in the state of Washington, *M. montanus* and *M. longicaudatus* are the main damaging species (Witmer and Proulx, 2010). The ecological counterparts of these species in Europe, *M. agrestis* and *M. arvalis*, are widely distributed and range from Fennoscandia, where they are mainly pests of forestry, to central and southern Europe, where they cause damage in afforestation, grassland and vineyards, and attack cereals and forage crops such as lucerne (Myllymäki, 1977a).

Damage to forestry is the principal form of agricultural loss inflicted by *M. agrestis* in temperate climes. However, in northwestern and central Europe, where *M. agrestis* and *M. arvalis* occur sympatrically, the latter usually starts colonizing afforestation at an early stage as soon as grasses cover the ground. Between 5 and 10 years after planting of the trees, *M. arvalis* is gradually replaced by *M. agrestis* (Niemeyer and Haase, 2003). Both species cause similar damage to young trees by debarking the base of the trunk, sometimes all the way down to the roots. If only partly debarked, trees may recover, but girdled trees die back.

Teivainen (1984) reported the results of a survey of losses by *M. agrestis* conducted over 8 years in Finland. Voles had influenced afforestation policy in causing the abandonment of the introduction of hybrid aspen (*Populus*) in an attempt to increase forest productivity. These trees were found to be particularly susceptible to damage by several vertebrate pests, including *M. agrestis*. Teivainen (1984) identified a number of factors that influenced the extent of damage. Damage to seedling trees was greater when they were planted in old fields that had been allowed to go to grass than in areas of forest that had been clear-felled and replanted. Of the main tree species planted in Finland, Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birches (*Betula pubescens* and *Betula pendula*), spruce was the least damaged by voles. Catastrophic losses occurred when susceptible birch and Scots pine were planted in vulnerable areas. Teivainen also noted that northern districts sustained higher damage than those in the south and that there were temporal fluctuations in damage levels, with vole populations increasing and decreasing in 3–4 year cycles. Of course, damage is most severe in years of peak vole density. Damage levels are also related to the age of trees, being lowest in plantations older than 9 years. Teivainen (1984) recorded damage in 2100 plantations, and observed that more than 30% of 7.2 million seedlings were damaged by voles.

Elsewhere, damage to forestry by voles follows similar patterns. Radvanyi (1972) recorded losses in conifer replantings due to voles in Canada. In some areas, reafforestation was almost impossible due to the consumption of broadcast seed and damage to seedlings. Seedlings planted in artificially regenerated stands are significantly more susceptible to damage than young trees that have naturally regenerated (Suchomel, 2008).

A compilation of data on vole damage in Europe by Jacob and Tkadlec (2010) suggests average losses of more than €10 million a year due to *M. agrestis* and *M. arvalis* in European agriculture, horticulture and forestry. In the peak year, 2007, damage by *M. arvalis* in cereals, grassland and fruit-growing areas led to a loss of sales of the order of €700 million in Germany alone. In the same year, Spanish farmers received €9 million as compensation for extensive damage by *M. arvalis* to cereal, potatoes and vineyards. The Spanish management cost was estimated at another €15 million (Jacob and Tkadlec, 2010).

Studies of voles as pests of agriculture in North America have focused largely on losses inflicted in orchards. In north-west USA, *M. montanus* is a severe pest in apple orchards. Losses in Washington State have been valued at US$33 million a year (Godfrey and Askham, 1988). Young trees are the worst affected. Voles feed on the bark and cambium of the trunk at the soil surface and also attack the root system. Such damage may result in lowered fruit yields, reductions in the size and quality of the fruit and the death of affected trees.

Elsewhere in the USA, particularly in the states along the eastern seaboard, *M. pennsylvanicus* and *M. pinetorum* inflict similar losses in orchards, the former generally attacking the tree trunk and the latter the root system. Byers (1974) estimated losses to be about 6% of the crop, valued at US$44 million in a year, whereas Sullivan *et al*. (1980) attributed 41% of fruit tree deaths in North Carolina to damage by *M. pinetorum*. In Canada, Brooks and Schwarzkopf (1981) found that 35% of apple trees sustained damage. In East Germany (the former GDR), Heise and Stubbe (1987) estimated the damage to apple trees caused by *M. arvalis* at about €25 million during outbreak years.

In northern China and Mongolia, populations of *M. brandti* occasionally reach plague proportions and inflict serious damage to pasture lands.

Myodes

Myodes is another genus containing some species of occasional pests, including *M. glareolus* in most parts of Europe (Lund, 1988) and *M. rufocanus* in Fennoscandia and in Hokkaido, Japan (Saitoh, 1987). As bank voles are more granivorous than the *Microtus* spp., outbreaks in temperate regions are often following mast seeding years of beechnuts and acorns (Pucek *et al*., 1993; Schnurr *et al*., 2002; Clotfelter *et al*., 2007). Due to its climbing abilities, *M. glareolus* often causes damage to the upper parts of trees. The extent of damage can be considerable (see Hansson and Zejda, 1977; Suchomel, 2006). However, the economic importance of damage by *Myodes* has been questioned, as population peaks are usually lower and damage is more scattered than that caused by *Microtus*. Hence, trees often recover and compensate for the damage (Krüger, 2002). In recent years, bank voles increasingly attract attention because they are reservoirs of *Hantavirus* (Puumala strain), which causes acute viral haemorrhagic fever, and high population densities make it more likely that the disease is transmitted to humans (Chapter 4).

Arvicola

The systematics of the genus *Arvicola* has been controversial and the status of a number of species, subspecies and morphs is still uncertain. We follow Musser and Carleton (2005), who discriminate three distinct species: *A. sapidus*, *A. scherman* and *A. amphibius*, the latter two being previously assigned as subspecies to *A. terrestris*. *A. sapidus* is restricted to parts of France and Spain, and *A. sherman* colonizes the highlands (between 200 and 1800 m) from the Cantabrian

Mountains in the west to the Carpathians in the east (Meylan, 1977). *A. amphibius* is found throughout much of western, central and northern Europe and Eurasia. The species still comprises two behaviourally distinct forms, a larger one associated with water and a smaller fossorial form. *A. scherman* and the fossorial *A. amphibius* are the most important from an economic point of view due to their wide distribution and devastating impact on certain farming activities.

High populations of *A. scherman*, sometimes exceeding 1000 voles ha^{-1}, occur in grasslands of the Alps and Jura mountains. When the animals excavate their burrow systems, they deposit the spoil on the surface where it reduces grassland productivity and contaminates foliage harvested for fodder. In a mixed sward, voles prefer the fleshy parts of herbs such as *Medicago*, *Taraxacum* and *Trifolium* but, when populations are high, they may inflict damage to plant cover such that pastures are useless for grazing and require resowing (Meylan, 1977). Such damage has been reported over tens of thousands of hectares during vole outbreaks in eastern France and Switzerland.

Fossorial *Arvicola* is also a serious pest of orchards throughout its range. Attacks often take place in the winter and may go unnoticed until tree death occurs. Fruit trees of all kinds are affected, but apple trees are especially vulnerable. Infestations of just a few animals can cause losses of considerable economic importance and, in severe attacks, 50% and more of trees may be lost in a single winter. A survey conducted by Walther *et al.* (2008) among organic fruit growers in Germany revealed that annual losses of 1–10% due to vole damage are common in organic pomiculture. With approximately 3000 trees ha^{-1}, this results in 30–300 damaged trees ha^{-1} annually. Depending on the age of the damaged tree (the economic lifetime of an orchard is about 15 years), the facilities of the orchard and the extent of damage (i.e. 1–10%), losses were calculated at a minimum of €870 and a maximum of €35,100 ha^{-1} annually.

Generally, the problems caused by the aquatic *Arvicola* form are limited to physical damage to the banks of canals and ditches caused by their burrowing. This is rarely serious enough to require remedial action, although orchards in land dissected by a drainage system may be prone to attack (Pelz and Gemmeke, 1988), and Dundjerski (1988) recorded a severe outbreak, with extensive resultant loss, in rice in Yugoslavia.

Biological and physical control

Few experiments have been conducted on the control of *Microtus* populations in forestry. Teivainen (1984) showed that 95% of the damage occurred during 2 years in which vole populations peaked. He recommended that extensive replanting schemes should be initiated in the year following vole crashes. This would allow seedlings to germinate and become established during periods of low vole density and, thereby, survive the period when they are most at risk. However, Myllymäki (1977a) considered the period of susceptibility to last about 10 years and it seems unlikely that plantings would be spared a vole outbreak over such a period.

Jobsen (1988) found that orchards established by immediate replanting and by planting in grassland were liable to attack by vole populations already present. He recommended deep ploughing to displace these residents and a 1 year break crop of cereals before setting out new orchards. In some areas, growers plant trees in containers of wire, 30 cm diameter and 25 cm high, with a mesh size of 1.3 cm^2, but this is very costly, and is often applied only to trees at the periphery of orchards that are particularly prone to attack.

The planting of species not much damaged by voles, such as Norway spruce, is also recommended to reduce losses. Roussi *et al.* (1988) found some birch hybrids to be significantly less likely to sustain damage than others, but it remains to be shown that this advantage, demonstrated in mixed plantings, is also exhibited in monocultures.

Usually, deciduous trees are more prone to damage than conifers. Niemeyer and Haase (2003) investigated vole abundance and damage to trees between 1989 and 2002 in afforestation with mixed deciduous tree species on former pasture and arable land in Holstein (north Germany). Despite several peak years with a high abundance of *M. arvalis*, serious damage of commercial relevance occurred in only one of the 12 afforestations examined. In this mixed stand of ash (*Fraxinus*), sycamore (*Acer*), beech (*Fagus*), lime (linden) (*Tilia*), elm (*Ulmus*), cherry (*Prunus*) and hornbeam (*Carpinus betulus*), vole damage removed most of the beech and hornbeam trees, while the other tree species suffered less from damage and recovered. The authors emphasize the value of mixed stands in afforestation practice, which may result in a closed stand comprising the remaining trees, despite the loss of beech and hornbeam. In all the afforestations observed, beech suffered the most from vole damage and oak (*Quercus*), sycamore and ash the least. Hopes have been built on the provision of alternative food to prevent voles from damaging trees, but a study on diversionary feeding with sunflower seeds in British Columbia (Canada) did not prevent voles (*M. montanus*) from damaging lodgepole pine seedlings, *P. contorta* (Sullivan and Sullivan, 2004).

Kaukeinen (1984) noted that before the 1920s most of the orchards in the USA were clear cultivated and suffered few vole problems. Later, to alleviate soil erosion and damage to fallen fruit, growers began cultivation practices that resulted in the establishment of dense grass cover, but these grasses improved the characteristics of the soils for burrowing and provided food and shelter for vole infestations. Cultivation practices are now recommended to reduce vole damage. Mowing, herbicide application, and a combination of both measures, significantly reduce vole numbers (Godfrey, 1987). Godfrey and Askham (1988) reported that frequent mowing had a dramatic effect in reducing vole activity in previously heavily infested orchards and resulted in an increased revenue of US\$7500 ha^{-1}. Mowing is not always practicable though, for example during the period when wooden props are required to support fruit-laden branches. The same authors showed that a plant growth regulator, applied at this time, reduced the height and density of ground cover, and they suggested that this measure would reduce vole populations.

The tendency in modern agriculture to increase the application of no-till can be very supportive of vole populations in improving their living conditions (Witmer *et al.*, 2009). Hence, in situations where fields are prone to vole damage, preventive ploughing in years of presumed outbreaks may be recommended (Jacob, 2003).

Trapping is an effective control method for *Arvicola*. Meylan (1977) found that a high proportion of individuals in fossorial populations could be captured quickly in a variety of traps. Although potentially effective, trapping is both labour and capital intensive and is useful only for small-scale control programmes (Pelz and Gemmeke, 1988).

Conventional biological control, involving the use of natural predators, has rarely proved effective. However, predators are thought to at least assist in reducing pest numbers, and investments are occasionally made in owl nest boxes, perches for raptors, heaps of stone or wood for weasels, or ladders for foxes to give them access to fenced orchards, as all of these animals are vole predators (Fuelling *et al.*, 2010).

Mechanical barriers are also used in high-value stands, such as in orchards and nurseries of grafted forest trees. The most common form to protect individual trees is a protective collar of either aluminium foil, hardware net or rigid plastic (Myllymäki, 1987). These are extensively used in Fennoscandia and proved highly cost-effective in protecting 1.5 million seedlings in a 3800 ha area in Finland (Myllymäki, 1977b). Based on the observation that young *Arvicola* usually disperse above ground (Saucy, 2002), Walther and Pelz (2006) successfully tested vole-proof mechanical barrier systems to fence complete orchards and, in that way, prevented voles from invading, once the area inside the barrier has been cleared of voles. Wire-mesh barrier systems proved particularly cost-effective if integrated into the game fence at the time of establishment of a new orchard. A further stage of such a barrier system has been developed by Fuelling *et al.* (2010). This system traps voles approaching the barrier and at the same time gives access to predators like foxes, weasels or cats that can easily prey upon the voles trapped in the system.

Devices that emit sounds of various wavelengths have been recommended for repelling voles (and moles, *Talpa europaea*) from their burrow systems, but none tested so far has been found to be effective (Pelz and Gemmeke, 1988; Pelz, 2003). Recent findings on the effect of species-specific calls on *A. amphibius* could be an option for future deterring measures (Menke *et al.*, 2008).

Chemical control

The use of rodenticides against voles is in a state of flux. There was a period when organochlorine insecticides with high mammalian toxicities, such as endrin, were used as ground sprays, but their application largely ceased when the active ingredients were banned because of their persistence in the environment. The literature contains conflicting accounts of the efficacy of many of the methods currently recommended and, as no single technique is wholly successful, an integrated approach is advocated.

Rodenticides are now not much used for the protection of forestry from damage by voles, and few products are registered for this purpose. Indeed, the use of rodenticides on an extensive scale in temperate agriculture is probably both impractical and undesirable because of the potential primary and secondary impacts on non-target species, according to the Convention on Migratory Species (CMS, 2013), which operates under the aegis of the United Nations Environment Programme (UNEP) (see also Chapter 16).

Two fundamentally different strategies were proposed for the use of rodenticides against vole outbreaks in Fennoscandian forestry. Stenseth (1977) modelled vole population dynamics and showed that, in theory, the chances of an outbreak could be reduced by the establishment of highly heterogeneous habitats and by the periodic widespread application of rodenticides. An alternative approach is that of Myllymäki (1987), who considered it possible to predict the locations of the vole foci that initiate outbreaks. He proposed the prophylactic treatment of these areas as a means of preventing the build-up of populations to damaging levels. Clearly, the latter is the more practical solution, but both are hampered presently by the fact that no fully effective and environmentally acceptable rodenticide treatments exist.

In contrast to the situation in forestry, the use of rodenticides for vole control in orchards is both long established and well researched, particularly in North America (Byers, 1974; Kaukeinen, 1984; Byers and Carbaugh, 1987; Hunter *et al.*, 1987). Liquid formulations, both of anticoagulants and of the acute toxicant endrin, have been used as ground sprays for vole control in orchards, though Byers (1984) showed these methods to be less effective and more costly than conventional baiting techniques. They are also environmentally undesirable because they use very large quantities of active ingredient, of which only a small proportion finds its way to the target animals.

In the USA, baits containing acute and anticoagulant rodenticides may be used by growers. This is because the economic threshold justifying their application is often very low. Byers (1984) estimated that the loss of a single established fruit tree in an orchard block of 50 ha is financially equivalent to the cost of treating the entire plot with bait. Baits are applied either by hand or mechanically, using an appropriately adapted spreader as normally used for granular fertilizers. The efficiency of hand baiting is increased when covers made from boards or old vehicle tyres are first put out beneath the trees and left for a few weeks. Vole activity is readily apparent when these covers are lifted, and the active sites are then treated. This technique has the important advantages of increasing cost-efficacy by reducing rodenticide usage, and of reducing the hazard to non-target animals (Kaukeinen, 1984).

A wide range of rodenticide active ingredients and formulations has been tested. Byers (1978) found anticoagulants to be generally effective in both laboratory and field trials, although results with diphacinone were unsatisfactory. In later trials of acute poisons (Byers and Carbaugh, 1987), calciferol performed well in the laboratory, but not in the field, and some formulations of zinc phosphide were found to be effective, whereas others were not. Byers (1984) examined the economics of rodenticide treatments for vole control. Generally, chemical control methods were less expensive than those involving the manipulation of the orchard environment, such as mowing, cultivation and the application of herbicides. Broadcast baiting was less labour intensive than the placement of rodenticides by hand, but proved equally expensive because of the larger quantities of rodenticides used. Anticoagulants performed more reliably than acute toxicants but required higher rates of application.

The use of rodenticides to control voles in the USA was reviewed by Witmer *et al.* (2009), who listed the active substances and baits approved by the US Environmental Protection Agency (US EPA) and described application methods and measures to be undertaken to mitigate risks to non-targets. Approved products contained the active ingredients zinc phosphide, the first-generation anticoagulants warfarin, chlorophacinone and diphacinone, and the fumigant aluminium phosphide.

In Europe, burrow fumigation is favoured for the control of fossorial forms of *Arvicola*, and the gases once applied included phosphine (Chapter 6), carbon monoxide and carbon dioxide. Pelz and Gemmeke (1988) considered the last to possess the best combination of safety, cost-efficacy and lack of polluting effect. However, fumigation is also work intensive, and for full effect gases must be introduced at several places in the complex burrow systems *of Arvicola* (Meylan, 1977).

The chemical control of *Arvicola* was also conducted using poisoned baits. Meylan (1977) considered *A. scherman* to be not very sensitive to anticoagulants, particularly chlorophacinone. Nevertheless, promising results were achieved with this compound against the aquatic form of *A. amphibius* (Pelz and Gemmeke, 1988) and also, against the fossorial form, with the more active compounds bromadiolone and difethialone (Lechevin, 1988). Pelz and Gemmeke (1988) found that proprietary baits were poorly accepted in the presence of alternative natural foods. Chopped fresh vegetables, particularly carrots, for instance, are readily taken and form the basis of successful control techniques for both the fossorial and terrestrial forms of *Arvicola*.

A specially adapted plough has been developed to construct artificial burrows for the control of *Arvicola* in orchards. These burrows, which efficiently intercept the voles' natural systems if the plough is set to the correct depth, are soon utilized by the voles. Anticoagulant-treated bait, deposited in the burrows as they are created, is encountered by the voles, which subsequently succumb to the poison (Jobsen, 1988). While bait application rates are relatively high (up to 40 kg ha^{-1}), both primary and secondary hazard to non-target animals is low because the bait is laid underground and the majority of voles die in their burrows. Even this method has a disadvantage though, as once constructed, the artificial burrows remain in the fields for some time and provide an attractive, ready-built habitation for returning voles. The aquatic form of *Arvicola* has also been controlled with anticoagulant-treated carrot bait when it is offered from floating bait stations (Pelz and Gemmeke, 1988).

In the European Union (EU), the use of rodenticides in open-field agriculture (e.g. against microtine voles) is regulated under legislation initially driven by the Plant Protection Products Directive (Council Directive 91/414/EEC concerning the placing of plant protection products on the market), and now subject to the Plant Protection Products Regulation (Regulation (RC) No 1107/2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC). The active substances zinc phosphide, bromadiolone, difenacoum and warfarin are approved. Presently, there are no rodenticide baits that are authorized for use in open-field agriculture against voles, although the review is not yet completed. Among the fumigants, only aluminium phosphide remains available for use in burrow fumigation (European Commission, 2012).

Chemical repellents have also been considered to prevent vole damage to trees (Witmer *et al.*, 2009). Registered game repellents proved mostly unsatisfactory in repelling voles. Studies on the repelling effect of secondary plant compounds, such as extracts from the globe thistle (*Echinops sphaerocephalus*), have recently sparked hopes (Fischer *et al.*, 2009; Heidecke, 2010). Such extracts showed strong effects in laboratory trials with *M. arvalis*, *M. agrestis* and *A. amphibius*. Repellents could be a future option to protect individual trees from damage by surface application and to deter *Arvicola* by volatile repellents applied to their underground galleries. Here, the challenge will be in formulating such repellents to make them sufficiently persistent and weatherproof.

The use of all rodenticide baits against microtine voles is problematic because these animals form the prey base of a wide variety of vertebrate predators in all ecosystems, and there is significant risk of secondary poisoning. It is thought that the second-generation anticoagulants put predators most at risk due to their high potency and persistence (Chapter 16). For example, applications of bromadiolone to control an outbreak of *M. brandti* in Mongolia in 2002 resulted in substantial non-target impacts (Winters *et al.*, 2010), and recent studies have shown that the first-generation anticoagulants may also present significant risks (Rattner *et al.*, 2011). This area is subject to ongoing review in the USA, EU and elsewhere. A workshop of the CMS concluded that the use of rodenticides, especially second-generation anticoagulants, in open-field agriculture is likely to present significant risk to migratory predatory birds (CMS, 2013). Those using rodenticides for the control of microtine voles must keep abreast of continuing regulatory changes.

Squirrels as Pests of Forestry

Distribution and nature of the problem

Among a worldwide total of approximately 245 sciurine rodent species, some 10% cause damage to natural forests and forestry plantations (Kuo and Ku, 1987). In North America, the damaging species belong mainly to the genera *Sciurus* and *Tamiasciurus*. The principal of these is *S. griseus*, which attacks plantings of ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) (Baldwin *et al.*, 1987). The red squirrel (*S. vulgaris*) causes damage to forestry throughout Europe and, in the UK, north Italy and southern France is joined by the grey squirrel (*S. carolinensis*), which was introduced from the USA. In Asia, particular attention has been given to damage to forestry on the island of Taiwan, where the Formosan red-bellied tree squirrel (*Callosciurus erythraeus*) and flying squirrels (*Petaurista* spp.) attack stands of Japanese cedar (*Cryptomeria*). These species, or their close relatives, cause similar damage on the Asian mainland and in Argentina.

Although squirrels may attack forest trees by consuming seeds, cutting down seedlings and clipping terminal shoots and buds, most damage of economic significance is related to their habit of stripping bark from the trunks and major branches of trees (Mayle *et al.*, 2007). Many different hypotheses have been put forward to explain this damage, but most are related either to behavioural or nutritional factors (Kenward, 1989). Behavioural explanations include the suggestions that stripping is done to mark territories, to obtain fibrous material for nests, during agonistic or courtship encounters, and as an uncontrolled reflex. Nutritional hypotheses focus on water deprivation, trace nutrient deficiency and a predilection for the sweet sap beneath the bark.

Studies of debarking by *S. carolinensis* in woodlands in the UK sought to identify parameters, both in the biology of the rodents and in the characteristics of the plantings, that were correlated with damage intensity (Kenward, 1989). The incidence of damage was highest in woodlands in which squirrel populations contained a high proportion of juveniles. This supported the hypothesis that debarking occurs during agonistic encounters as young animals attempt to establish territories. However, the parameters that best correlated with damage levels were associated with the trees themselves, rather than with the pests damaging them (Mayle *et al.*, 2007, 2009). Certain tree species were generally preferred in mixed stands, and broadleaved trees, such as beech and sycamore, always sustained the most damage. Specimens that generated the greatest flow of sap were those most frequently attacked among susceptible tree species. Trees with phloem less than 0.3 mm thick were sampled, as demonstrated by the removal of small bark flakes, but were not damaged further. Trees with a greater thickness of phloem tissue were often more extensively damaged and this occurred mainly during midsummer in trees of 10–40 years of age.

Squirrel debarking may have a variety of effects on the damaged tree. Trees that are ring barked, or girdled, at a low level may be killed outright, whereas damage higher up may cause the death of the crown or deformations that lower the value of the affected tree for timber. Repeated attacks reduce the vigour of the tree and, hence, timber yield. Attack may also have indirect effects on timber quality due to resultant infections with decay and wood-staining fungi. Few quantitative assessments of the value of these losses have been made, but Kuo and Ku (1987) estimated that, in Taiwan, timber production was reduced by as much as 10% in heavily debarked plantings. In the UK, the cost of grey squirrel damage to beech, oak and sycamore alone was estimated as £10 million in an unpublished report from 2001 (see Mayle *et al.*, 2009). A potential reduction of up to 50% in value of the final crop is considered possible in places.

Biological control

Studies of the susceptibility of forestry plantations to squirrel damage, and of the influence of such factors as husbandry practices, tree species composition and tree quality, have provided a foundation for predictions of the likelihood of squirrel damage in time and space (Kenward, 1989). In Europe, broadleaved plantings are most vulnerable between the ages of 10 and 40 years and above 7.5 cm diameter at breast height. Before this, the phloem is too thin and the sap flow insufficient to be attractive to squirrels, and after this, the protective bark is too thick. Kenward (1989) has also shown that the trees remaining after thinning become particularly susceptible 2–3 years after this operation because, at that time, they begin actively to grow away again. Plantation trees have thicker phloem than self-set trees and the former are, therefore, more susceptible at all stages of growth. In this context, the preponderance of self-set forests in North America may explain the fact that squirrel damage there is rarely important, despite the abundance of squirrels. In contrast, in the UK, Mayle *et al.* (2009) showed that both naturally regenerated and planted stands were prone to damage by grey squirrels, particularly when growing vigorously.

These observations have led to proposed strategies for the management of squirrel damage. For example, any move towards plantation forestry in the USA should be avoided because increased squirrel damage will certainly occur. Kenward (1989) proposed a system of plantation husbandry in which seedlings are planted and establish themselves below a canopy of mature trees. This would ensure that the phloem tissue remains thin and unattractive until the trees are mature and possess a thick layer of protective bark. It seems doubtful, though, that this scheme could be compatible with current requirements for rapid tree growth to achieve fast financial returns from investment in forestry.

Physical and chemical control

Physical methods for controlling squirrels, such as trapping and shooting, are widely practised and sometimes achieve substantial culls. However, it is generally recognized that these methods are both resource intensive and have limited durations of effect on squirrel populations and damage levels (Gurnell and Pepper, 1988).

In the UK, a poison-baiting scheme has been developed (Rowe, 1980) in which the anticoagulant warfarin is presented from feeding hoppers that are specially designed to limit access to non-target animals, which are often abundant in forestry. The application of this technique is strictly controlled by legislation, both from the UK authorities and in the EU, and is prohibited in areas where the threatened red squirrel (*S. vulgaris*) occurs. Much emphasis was given to target more precisely vulnerable areas at times of a high likelihood of damage occurrence (Gurnell, 1989). It is recognized that, like physical control methods, the effectiveness of baiting is transitory. Because damage in the UK is restricted to the June and July months of maximum sap flow, it is profitable only to apply bait at that time, and in the period immediately preceding it. Also, placing bait in areas that are susceptible to damage may be counterproductive. Warfarin is a slow-acting poison and much damage may be done to trees by squirrels attracted to feed at bait hoppers, but before a lethal dose has been taken. It is better, therefore, to bait areas with high squirrel densities but which are less vulnerable to damage (see Mayle *et al.*, 2007). These areas then become 'sinks' into which animals from vulnerable habitats are drawn. Proposed management strategies are now based on these considerations, and also on an ability to predict with reasonable accuracy the probability of damage occurring, which is based on estimates of squirrel population parameters, such as early season breeding, high juvenile recruitment and population density (Mayle *et al.*, 2007).

It seems likely that these methods, developed and recommended for the control of grey squirrels in the UK, could be adapted for use in other countries where this and closely related species are pests of forestry. For example, hoppers like those used for the administration of warfarin have proved effective, with brodifacoum bait, for the control of *C. erythraeus* in Taiwan. The efficacy and practically of physical and chemical methods for the control of grey squirrels in UK forestry was extensively reviewed by Mayle *et al.* (2007), and their conclusions are broadly relevant to other pest species found elsewhere, although in the longer term, the authorization of warfarin for squirrel control in the UK will be withdrawn. The EU Plant Protection Products Regulation (European Commission, 2009) makes necessary the review of all chemicals used in plant protection, including warfarin. The prospective cost of the review exercise, reported to be a minimum of €460,000, is currently disproportionate to the commercial value of the market, and so yet another useful chemical intervention for rodent pest management will be lost due to the inflexible rules of the European Commission.

The Mouse Plagues of South-eastern Australia

Distribution and nature of the problem

Without doubt, the most spectacular manifestations of rodents as pests of temperate agriculture are the outbreaks of house mice that periodically reach plague dimensions in the south-eastern states of Australia. The first plagues were recorded about 100 years ago and they have recurred on average 1 in 7 years ever since (Brown *et al.*, 2010). Population data exist for the extreme eruptions that took place in 1979–1980, 1984, 1993 and 2011.

The taxonomy of the genus *Mus* is complex, and multiple introductions into Australia from both Europe and the Far East may have resulted in considerable genetic variation among mouse stocks. However, populations studied during outbreaks are now attributed to the subspecies *M. musculus domesticus* (Musser and Carleton, 2005). House mice are distributed throughout Australia, while massive upsurges, reaching up to 2700 individuals ha^{-1}, are largely restricted to the south-eastern wheat belt from southern Queensland to South Australia (Singleton *et al.*, 2005).

The impact on human activities of mouse plagues is both economic and sociodomestic (Redhead and Singleton, 1988). The economic effects involve losses to standing crops and to a wide variety of stored products, and also the destruction of property, possessions and infrastructure. The cost of the 1993 outbreak was estimated at A$64.5 million from a survey of grain growers in Victoria and South Australia (Caughley *et al.*, 1994). The annual cost impact, including agricultural production loss, management and research, was estimated at A$35.61 million year^{-1} (McLeod, 2004). The 2011 plague spread across four States (New South Wales, Queensland, South Australia and Victoria), and in New South Wales alone, the Farmers' Federation estimated that 3 million ha of crops were affected. For an overview of mouse abundance and damage, see Brown and Singleton (2002).

The invasion of farmsteads and townships by hoards of mice is extremely distressing for their occupants. It has been argued that the socio-domestic trauma suffered by those affected is, of itself, sufficient reason to justify the attempt to solve this problem.

Causes of mouse plagues

Several hypotheses have been put forward to explain the causal mechanism of mouse plagues. All propose roles for unusual weather events, usually rainfall, stimulating the availability of high-quality food supply, and the high reproductive potential of house mice (Redhead *et al.*, 1985; Redhead and Singleton, 1988; Singleton, 1989).

In non-plague conditions, house mice occur as small populations living in suitable habitat patches. Populations build up in these 'donor' areas and mice disperse from them into suboptimal 'reception' habitats. In most years, these do not provide the conditions necessary for breeding. However, unusual rainfall occurs in some years, particularly in the autumn, and this induces further growth of vegetation, providing protein-rich food for mice and stimulating prolonged reproduction. When enhanced reception habitats allow breeding, they become 'induced donor' habitats.

In southern Australia, these events are the 'plague trigger' and initiate the first plague phase. Next spring, mice are more abundant than usual and in better reproductive condition. Because of this, productivity is very high during the following summer, and the mouse population quickly increases in this second phase of the outbreak. It reaches a peak during the late autumn and early winter and the mice disperse widely to cause substantial damage in crop areas, the so-called 'impact' habitats. Many mice may die during the second winter and the outbreak may subside. Under some conditions a third phase may occur in the following year when mouse populations reach a second peak and inflict further serious losses. Further north, in south-east Queensland, there are two cereal crops a year, which provide sufficient high-quality food for mouse plagues to occur within 9 months (Singleton *et al.*, 2005).

This model may be overly simplistic (Brown *et al.*, 2010), as although outbreaks never occur after droughts, they are not always triggered by good winter rainfall. Moreover, supplementary food or water supply in field experiments did not stimulate reproduction in low-density populations. Brown *et al.* (2010) concluded, based on a study by Sutherland and Singleton (2006), that additional processes concerning the breakdown of the social organization of house mouse populations may be required to induce an outbreak, rather as they are in northern hemisphere vole outbreaks (Krebs, 2013).

Control strategies

Current practice in the control of mice is the application of zinc phosphide-coated wheat grains within crop fields. Second-generation anticoagulant rodenticides are registered in some Australian states for use at field margins using bait stations only. During outbreak years, these measures may be successful in reducing mouse numbers over limited areas for short periods, but immigrants from nearby untreated donor habitats rapidly repopulate the treated fields. It is widely recognized that these measures fail because they are applied too late (i.e. only when large mouse populations are already apparent). At that time, the outbreak mechanism is under way over extensive areas and cannot be averted by any form of human intervention. Instead it is recommended to take early action based on model predictions.

A number of predictive models have been developed for assessing the relative merits of control measures (see Pech *et al*., 1999). The most recent of these predict either the population density in house mice (Pech *et al*., 1999) or the likelihood of the occurrence of a massive outbreak (Kenney *et al*., 2003; Stenseth *et al*., 2003). Predictions are based on weather observations (April–October rainfall as the 'plague-trigger'; see also Krebs *et al*., 2004), and on the density and breeding condition of mouse populations in October (spring). Such models achieve 70% accuracy in predicting an outbreak in the autumn, based on data gathered during the previous spring. An important difficulty in such predictions is that they will be attempting to stimulate management actions when no obvious problem is yet apparent. Davis *et al*. (2004) suggested that it is economically beneficial for farmers in south-eastern Australia to take pre-emptive action when the probability of an outbreak is ≥0.3, a threshold corresponding to the assumptions of the models developed for southern Australia. However, Brown *et al*. (2010) point out the lack of appropriate surveillance and population monitoring that is required for the operation of predictive models.

Control measures would be applied with one of three aims: (i) to reduce the numbers of mice available to enter impact habitats from donor and induced donor patches; (ii) to prevent their entry into impact habitats such as crop fields and farmsteads; and (iii) to reduce their numbers when they have gained entry. The responsibility for conducting control measures will generally rest with individual farmers and managers, whereas neglected areas, such as roadside verges, watercourses and uncultivated land, which frequently act as donor and refuge habitats, will require the intervention of some central authorities for proper treatment to occur. The emphasis of effective management is, therefore, on broad-scale community action (Brown *et al*., 2004).

A variety of control options is available. Those applied at the early stages of the outbreak would mainly comprise habitat modifications such as, in cereals, increased sowing depth, careful selection of harvesting times and stubble management to remove crop residues. Reduction of cover and potential food by mowing, grazing or herbicide spraying in the margins of crops has proved effective (Brown *et al*., 1998). On farms, the removal of harbourage and the rodent proofing of food sources would serve to reduce their suitability as refugia. As the mouse populations build up and begin to move, they may be excluded from impact sites by barriers, properly designed storage structures, repellent devices and perimeter baiting. Once standing crops are infested, the only practical control measure is in-crop baiting with zinc phosphide, using fertilizer spreaders or aerial application.

There have been significant efforts to develop fertility control for the house mice of Australia by immuno-contraception using a recombinant mouse-specific virus to deliver antibodies that inhibit fertilization to female mice (see Hardy *et al*., 2006 for review). Long-term infertility could be induced in laboratory trials, but the rate of virus transmission to wild mice under laboratory conditions was poor (Redwood *et al*., 2007). There were also concerns about the release of such a modified organism and the risk of its accidental export to other parts of the world where non-target mouse species might be infected (Williams, 2005; Fisher *et al*., 2007).

Ground Squirrels, Prairie Dogs and Marmots as Pests of Rangeland in the USA

Distribution and nature of the problem

Cattle ranching is an essential component of the agricultural economy of many western states of the USA. Rodents of three sciurid genera, *Spermophilus*, *Cynomys* and *Marmota*, are abundant throughout the area and present a serious threat to forage production in these important rangelands.

Many species of *Spermophilus* (ground squirrels) occur, and seven are accorded pest status (Marsh, 1984). These animals inhabit large areas, including the open grassy plains of the arid west, and attack pasture, cereals and horticultural crops, as well as being serious pests of rangeland. They are also a danger to public health because they carry a number of diseases transmissible to humans, including plague (Barnes, 1990). Ground squirrels are social animals living in colonies which tend to spread slowly, but populations eventually build up to reach densities exceeding 120 ha^{-1}. The animals hibernate through the winter and emerge in spring to feed on the young shoots of range herbs and grasses. Later in the season, as the plants desiccate, the squirrels switch their feeding to the dry parts of plants, particularly the seeds.

Estimates have been made of the impact of ground squirrels on range productivity (Marsh, 1984, 1998). Clearly, this is influenced by the species involved and the density of the squirrel populations. Californian ground squirrels (*S. beecheyi*), at a density of 12 ha^{-1} in experimental plots, consumed 1121 kg ha^{-1} of forage or 30% of the total production. It is also estimated that 355 Columbian ground squirrels (*S. columbianus*) consume in a day forage equivalent to the requirement of a sheep and, similarly, 200 *S. beecheyi* eat an amount sufficient to feed a 454 kg steer. Forage production in marginal rangelands is often sufficient to support only low rates of stocking. In these cases, ground squirrel populations may have a significant detrimental effect on the viability of ranching enterprises. Adverse weather conditions can further exacerbate the problems. The potential impact of ground squirrels is demonstrated by the extent of ground squirrel control activities in California. It was estimated that, in 1982, 2–2.5 million ha of rangeland received treatment for ground squirrel infestation (Marsh, 1984). More recently, in western Canada, populations of *S. richardsonii* reached epidemic levels and seriously compromised rangeland economy over large areas. A combination of factors caused this outbreak, including drought, poor grassland management, inefficient rodenticides and a reduction in predator numbers (Proulx, 2010). Witmer and Proulx (2010) also reported that drought resulted in an outbreak, with *S. richardsonii* densities often exceeding 40 animals ha^{-1} in the prairies of southern Canada and north-central USA. The impact of this outbreak was boosted by overgrazing as a result of increased numbers of cattle, and resulted in serious problems in livestock breeding in the area.

Prairie dogs (*Cynomys* spp.) are also pests of rangeland, but they are less important than ground squirrels. It was estimated that these animals once occupied a range extending from Mexico to Canada and totalling some 40 million ha. However, farming practices and intensive control programmes brought about a dramatic reduction in the area they inhabit – to about 600,000 ha (Summers and Linder, 1978), although numbers are increasing once more. Prairie dogs are larger than ground squirrels and do not hibernate. They prefer short grass plains, and livestock grazing makes otherwise unattractive habitats more suitable for them. They are highly social, living in colonies, or 'towns', sometimes comprising several thousand individuals and covering hundreds of hectares. At its peak, population density reaches 200 ha^{-1}, but 50–60 ha^{-1} is more normal. Prairie dog burrow systems may be very complex and entrances are characteristically surrounded by raised mounds. The competition of prairie dogs with livestock for forage has been extensively studied. For example, Hansen and Gold (1977) found that a mixed community of these animals and cottontail rabbits (*Sylvilagus audubonii*) reduced range productivity by about 25%. Other estimates have demonstrated a more dramatic effect (Marsh, 1984) and, as with ground squirrels, competition with stock for forage is more pronounced in drought years.

The genus *Marmota* is represented by six species in North America. These animals, the largest of the sciurids, live in marginal areas, such as rock outcrops, ravines and along fence lines. Their effect on agriculture is limited but they may cause serious damage where they are locally abundant. They consume crops of all kinds and, due to their size, the impact of a few individuals may be considerable.

Control of rangeland rodents

The control measures used against ground squirrels, prairie dogs and marmots are generally alike. The most cost-effective means of controlling extensive infestations of these animals is the application of poisoned baits, and this method is most often employed against ground squirrels. Here, recent regulatory restrictions on the use of rodenticides against these pests, mostly driven by concerns about environmental impacts, have resulted in a reduction in the number of rodenticides available. Trapping, shooting and burrow fumigation are also used in the management of small numbers of animals, particularly the larger species of prairie dogs and marmots (Salmon and Schmidt, 1984; Van Vuren *et al.*, 1997).

An integrated approach to the management of rangeland rodents is always to be recommended, and a thorough understanding of pest biology is essential (Marsh, 1984; Howard *et al.*, 1990; Proulx, 2010). For example, the timing of bait applications in relation to the annual cycle of activity and reproduction is particularly important in ground squirrel control, and this may vary with local conditions (Marsh, 1994). These animals hibernate throughout the winter and emerge in early spring. Breeding begins within about a month of emergence and baiting is best conducted before it gets under way. At this time, the animals are foraging on fresh green vegetation. Dry baits are not readily taken, but baits formulated on chopped lucerne and cabbage are very attractive. At high altitude, and in some northerly latitudes, the squirrels may emerge before adequate food is available and baiting is then particularly effective. If ground squirrel control is to be applied during breeding, trapping and burrow fumigation with aluminium phosphide may be effective (Baldwin and Holtz, 2010).

The rangeland herbage dries up after the ground squirrel breeding season, and the animals then feed almost exclusively on seeds. They must forage actively, and cereal baits, usually based on oats or barley, are readily accepted and consequently highly effective. Baiting is conducted by hand, either on foot, from horseback or from all-terrain vehicles, by vehicle-mounted spreader or, occasionally, by aircraft. Hand baiting directly into burrows offers the best option to avoid primary poisoning of non-targets, but ground squirrels often clean their burrows after baiting and eject bait on to the surface (Proulx *et al.*, 2010).

Acute poisons, such as strychnine, compound 1080 (sodium fluoroacetate) and zinc phosphide, were once widely used for the control of rangeland pests because of their low cost. However, the use of compound 1080 in rangeland, and elsewhere, was not defended in the EPA review of rodenticides, and all registrations for the compound have now been withdrawn. An effort was made by user groups and manufacturers to maintain certain applications of strychnine in Canada and the USA, but this rodenticide is no longer registered as the sulfate, and only subterranean uses of the alkaloid are currently permitted (Jacobs, 1992; Proulx *et al.*, 2010). Salmon *et al.* (2000) reported trials showing variable efficacy of zinc phosphide baits against *S. beecheyi*, with effectiveness influenced by timing of the bait applications, the use of prebaiting, availability of alternative food and other factors. In Canada, Proulx *et al.* (2010) reduced the non-target impacts of strychnine baits by presenting them in a multi-capture pen trap accessible only to ground squirrels.

The early anticoagulants, such as warfarin and diphacinone, were not much used on rangeland because they required repeated applications and this was prohibitively expensive (Marsh, 1984). Later on, with some acute poisons no longer available, the anticoagulant options were re-evaluated. For example, Hazen and Poché (1992) showed chlorophacinone to be effective for the control of *S. beecheyi*. More recently, Salmon *et al.* (2007) found that chlorophacinone baits remained effective after a reduction of the concentration of active ingredient proposed by the EPA to reduce non-target risks. Other measures to reduce non-target risks, such as increasing the interval between bait applications and a reduction of their number, also did not impair control efficacy (Whisson and Salmon, 2002a,b). However, Whisson and Salmon (2009) found that another mitigation measure, the use of bait stations, did adversely affect efficacy.

A means of reducing the non-target impacts of anticoagulants against ground squirrels was suggested by Salmon (2010). He proposed that applications of diphacinone should be preceded by the use of zinc phosphide baits in order to reduce the numbers of animals affected by the more persistent rodenticide.

During the recent outbreak of Richardson's ground squirrel (Proulx, 2010; Witmer and Proulx, 2010) misuse of poison baits led to a depletion of predator populations and further impaired the difficult rodent-control situation. Consequently, Witmer and Proulx (2010) called for a long-term management programme that would integrate sustainable grassland management with the effective conservation of mammalian predators and the sensible use of effective rodenticides.

This discussion has concentrated on ground squirrel control, and has reflected upon the extensive research done on the management of these animals. Prairie dog and marmot populations tend to be less extensive and, therefore, are more frequently controlled by techniques targeted at their burrow systems. Fumigants are widely used and are most effectively applied in spring when soil moisture assists the retention of the poisonous gases in treated burrows. Trapping is advocated in areas where the application of rodenticides poses unacceptable hazards to non-target wildlife. Many types of traps are available and, apparently, they differ little in their efficiency (Edge and Olsen-Edge, 1990). Baiting is often conducted by hand; small quantities of bait are usually placed outside burrow entrances because baits put inside them are not effective. Zinc phosphide is used successfully with prebaiting against *Cynomys*, but is not as efficient as strychnine. It seems that, for the time being at least, the effective control of rangeland rodents will be increasingly problematic, possibly to the extent that these animals will again pose a serious threat to ranching activities in the west of the USA and Canada (Marsh, 1984; Witmer and Proulx, 2010).

Conclusion

The rodent pests of temperate agriculture examined in this chapter were chosen to exemplify a range of pest problems and control strategies. Although differing in detail, the schemes described are similar in that they aim to integrate a number of appropriate control methods. Excellent research has provided a good understanding of the biology of some of these problems. This has enabled those planning control programmes to identify a number of habitat manipulation mechanisms to make agroecosystems less amenable to rodent infestation. In most cases, a thorough knowledge of the biology of the pest allows pest controllers to apply rodenticides when they are likely to be most effective. Rodenticides feature strongly in all of the schemes but, for a variety of reasons, are the complete answer in none.

Natural enemies are important elements of integrated pest management (IPM) schemes for insect pests, but it seems unlikely that predators can play a central role in most rodent management programmes (see Chapter 1). Rodents form the prey base of many predator–prey relationships in natural ecosystems and, in isolated communities, this may have an important impact (e.g. Kildemoes, 1985). In contrast, in the extensive monocultures that characterize many agroecosystems, the ecological scales are usually tipped so strongly in favour of rodents that predators are unable to prevent outbreaks. Nevertheless, the preservation of predator populations may provide an important adjunct to other measures (Jacob and Tkadlec, 2010; Witmer and Proulx, 2010).

A prerequisite of IPM schemes is a decision-making procedure that allows pest management to be initiated in a timely and cost-effective fashion (Chapter 13). Much research effort has been dedicated to the development of methods for forecasting outbreaks of house mice in Australia (Pech *et al.*, 1999), of *Arvicola* in continental Europe (Pascal, 1988), of microtines in Fennoscandia (Myllymäki *et al.*, 1985) and of grey squirrels in the UK (Mayle *et al.*, 2007). These studies provide a basis for an improving ability to plan and implement control action before rodent populations have reached damaging dimensions. However, in none of the cases described here can the rodent pest problem be said to have been truly solved. More work is required to develop methods that are more practical, less costly and exert fewer adverse effects on the environment. As regulatory pressure continues to mount on both anticoagulants and acute poisons, it is likely that even fewer solutions that employ rodenticides will be available than are presently used.

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13 Rodent Control in Practice: Tropical Field Crops

M.W. Fall and L.A. Fiedler
Formerly of National Wildlife Research Center, USDA Animal and Plant Health Inspection Service, Fort Collins, Colorado, USA

Introduction

This chapter is a revision and update of material presented in the first edition (Fiedler and Fall, 1994). In 1994, we believed that examples of long-term successes in reducing rodent damage to tropical crops were very limited. At the time, the situation was blamed on insufficient information that had, over previous decades, precluded specific recommendations. Beginning in the late 1960s, several research projects, primarily focused in Asia, investigated important crop loss situations and demonstrated several effective rodent-control methods. Moreover, these findings and some control recommendations were published and incorporated into extension programmes in a number of areas. Most of the publications concerned were in widely available 'grey literature' or in conference proceedings because few journals were available with an interest in applied vertebrate pest control research – and even those were not available to managers, researchers or extension personnel in problem areas. Despite this progress in the development of rodent-control methods, the adoption of new methods by farmers has been slow, even in areas where intensive efforts were made to introduce new procedures (Quick, 1991). Problems associated with changing traditional rodent-control practices paralleled those encountered with the introduction of other new crop production technologies to tropical agriculture.

In updating our chapter, we searched the literature published since the 1994 edition, using the databases 'Wildlife & Ecology Studies Worldwide' and 'Google Scholar'. We used the search terms 'rat control' and 'rodent damage control', successively combined with 'cacao, cocoa', 'coconut', 'fruit', 'maize', 'corn', 'oil palm' and 'rice'. Because much of the post-1994 literature on rodent control in tropical crops has been generated by just a few investigators and their colleagues, we also searched selectively by author names and further searched the Rice Bibliography of the International Rice Research Institute (IRRI). Collectively, these searches resulted in several hundred thousand entries, though of course, with much redundancy. We examined the first 100 entries in each search, removed redundancy, then further eliminated papers that by title or keywords focused on damage observation or description, strategic or philosophical discussion, or anecdotal or promotional material rather than on the evaluation of actual control methods. We added several older papers to the list that we did not examine in 1994, resulting in about 200 new publications that we then read for content. We were surprised that relatively few papers focused on the practice of rodent control compared with the large number devoted to describing an already well-known problem of rodent damage to crops or promoting anti-pesticide approaches to problem resolution.

Practical rodent pest management methods are now available for tropical crops in many areas, usually involving combinations of cultural practices and the strategic use of environmentally safe rodenticides. However, rodent species differences and ecological differences in crops and cropping practices in different areas still require the evaluation of methods in new practical use situations (Wood, 2001). In our earlier review, published work on rodent control, a reflection of the overall research effort, was minimal, particularly in Central and South America, the Caribbean, Africa, the Middle East and the Far East (Kaukeinen, 1987). While the amount of new, practical information has increased somewhat, most current work continues to emphasize problem description or re-description rather than moving forward with the development of new practical rodent-control methods, thus leaving the continuing use of rodenticides the primary method of rodent damage control (Buckle, 1999; Singleton *et al.*, 1999a; Stenseth *et al.*, 2003). Although relatively more publications, particularly on African rodent damage problems, have appeared (Leirs and Schockaert, 1997; Makundi *et al.*, 1999), there are still a number of important crop damage situations for which no generally accepted rodent-control methods appear to be available or widely used (ICRBM, 2006).

Rodent Problems

Annual chronic losses

Rodent damage situations can be highly variable, often seasonal, unevenly distributed and difficult to predict (Fiedler *et al.*, 1991). Many rodent species are inactive during the day and are, therefore, not readily observed by farmers, extension workers or researchers. Damage can be concentrated and obvious, such as the 1–2 m diameter circles of cut wheat tillers surrounding burrow openings of bandicoot rats (*Bandicota bengalensis*); or it can be widely dispersed and cryptic, as in rice fields in South-east Asia with less than 10% damage. The latter damage pattern frequently goes unobserved by both farmers and crop protection specialists unless they examine plants closely.

The perception of a problem and of the actual damage or loss occurring can be very different, erring in either direction. For example, farmers in Indonesia appeared to be satisfied with their harvest before learning that their rice fields actually had more than 7.5% cut tiller damage and 0.64 t ha^{-1} lower yields than fields baited with rodenticides (Buckle, 1988). Also, without the benefit of actual damage assessments, crop protection specialists and Filipino farmers disagreed on the pest status of rodents in rice fields (Litsinger *et al.*, 1980). These examples demonstrate the importance of the physical examination of individual plants to assess rodent damage and the need to examine yield losses.

Estimating crop damage and relating the results to yield loss is often confounded by variations caused by plant compensation and different fertilizer inputs, insect pest and weed problems, and inadequate damage assessment techniques (see Chapter 10). Nevertheless, chronic losses that occur annually in tropical field crops as a result of rodent damage are probably 5% or more (Hopf *et al.*, 1976), even when traditional rodent-control methods are practised. Locally, chronic losses can be much higher (Jackson, 1977), particularly when crops are grown in areas that are highly susceptible to rodent damage. When these chronic losses occur continually over large areas, they are more significant than the more obvious outbreak losses that receive national, and sometimes international, attention (Buckle *et al.*, 1985; Leirs *et al.*, 1999; Stenseth *et al.*, 2003).

Periodic acute losses

Outbreaks of losses in agricultural areas that result from unusual rodent population increases can be dramatic and extremely visible, and can occasionally result in food shortages over large areas. There are two primary types of rodent population outbreaks. One type occurs after new areas are opened to agricultural production; another type results from major climatic changes involving a period of either excessive rainfall or, more commonly, abnormal drought followed by normal rainfall (Fiedler, 1988b; Leirs *et al.*, 1990; Singleton *et al.*, 2010a). Lengthy drought not only reduces rodent populations but also changes the influence of factors that normally limit their numbers – predation, competition and disease. Resumption of rainfall provides an immediate abundance of food, shelter and water for surviving rodents, so that increased reproduction, survival and dispersal occur. Rodent outbreaks in Australia and Hawaii involving *Mus musculus* occur after lengthy droughts are ended by normal rainfall (Tomich, 1986; Ramsey and Wilson, 2000). Australian wheat crops have been seriously affected during these mouse plagues (see Witmer and Singleton, 2010; and Chapter 12). Rat population irruptions involving bamboo flowering are related in that abundant food becomes available in areas with previously limited resources (see Chapter 3). As the food base again declines, surviving rodents may shift their activity ranges into cropping areas (Jaksic and Lima, 2003; Singleton *et al.*, 2010b).

Reports of rodent outbreaks in Africa have been more frequent, extreme and widespread than in other tropical areas. Two or more periods of favourable rains, after a period of low rodent population density resulting from drought, characterized outbreaks in Senegal (Hubert and Adam, 1985; Leirs *et al.*, 1990, 1996). Similarly, the 1986–1987 outbreaks in Sudan and some other Sahelian countries occurred after a 4–7 year drought was interrupted by normal rainfall in 1985 and 1986 (Fiedler, 1988a). Over a 12–18 month period, high rodent populations developed but went unnoticed by authorities until complaints from farmers reached a peak. In remote areas, subsistence farmers were forced to replant fields several times before any assistance was begun.

Common characteristics of tropical rodent problems

Although each tropical rodent damage situation deserves individual attention, there are some general characteristics that are shared. Most rodent pest populations express seasonal trends in activity, reproduction and abundance which are related to crop phenology and climate. Alternating dry and wet seasons influence not only crop planting schedules but also rodent breeding, mortality and mobility. Successful damage control programmes have identified these seasonal trends and used the information to help determine when crops are most susceptible to damage and when rodent pests are most susceptible to control. Because habitats adjacent to crop fields, orchards or plantations generally provide food and cover throughout the year, rodents may breed continuously in these areas, invading fields when crops are susceptible to damage. Such refugia may present special problems of access and the exposure of non-target animals if rodent control is attempted outside field margins.

When habitats are disrupted, resident rodents may move to more favourable surroundings. Disruptions may be caused by fire, flooding (including patterns of irrigation), drought and agricultural practices such as land preparation and harvesting. During dry seasons, irrigated croplands attract rodents from surrounding, less favourable habitats. Knowing how adjacent habitats influence rodent damage in susceptible crops is essential for effectively managing rodent pest problems.

Control Methods

The primary objective in any agricultural rodent pest management programme should be cost-effective crop protection, hence lower damage and higher yields. Using numbers of rodents or indices of rodent abundance before and after control operations is only useful for determining changes in populations or activity. Unless it has been adequately demonstrated that reduced populations result in reduced damage in a particular situation, changes in rodent numbers should not be relied on to estimate the degree of crop protection achieved. Even though reducing local populations may achieve higher yields in many situations, in some, the yield increase may be relatively costly. For example, crown baiting in Philippine coconut plantations is more cost-effective than ground-baiting methods (Fiedler *et al.*, 1982). Targeting those rodents that are actually doing the damage increases efficiency and raises the economic benefits of control by lowering costs. Effective control programmes have been based on ecological or behavioural research that identified the vulnerable factors in the behaviour and life cycles of rodent species and have used this information in the development of materials, methods and procedures to protect crops. For example, sustained baiting to protect rice from rodent damage involved adjusting the numbers and locations of bait stations to manage feeding competition and relate bait presentation to crop stage and damage potential (West *et al.*, 1975; Fall, 1977; Hoque and Sanchez, 2008).

Many rodent-control problems involve only a single pest species. Further, in multiple species situations, it is possible for a minor rodent species to assume a greater role in crop damage when populations of a primary species are reduced or when seasonal habitat changes no longer favour the primary species (Wood, 2001). For a situation involving rodents and larger mammals, such as bandicoot rats and golden jackals (*Canis aureus*) inhabiting Bangladesh sugarcane fields (Sultana and Jaeger, 1992), a systems management approach may be helpful (Watt, 1970). However, systems approaches are expensive and time-consuming to develop and, without widespread adoption, the development costs would probably not be recovered (Hygnstrom, 1990).

Chemical

Rodenticides are generally an integral part of successful rodent pest management and, in some tropical habitats, are the only practical method available (Buckle, 1999). Unfortunately, farmers and extension personnel are often confused or uninformed as to how a particular product may be effectively used. Local labels typically lack adequate use directions and provide only generic instructions that leave users guessing or improperly improvising untested application methods. Fortunately, a number of companies that service international rodenticide markets are now providing better information and technical assistance for tropical countries.

There are two basic field methods currently recommended for applying rodenticide baits. Both the sustained baiting method, with multiple-dose anticoagulants, and the pulsed-baiting method, with single-dose anticoagulants or acute rodenticides, can be cost-effective in specific crop situations (Wood, 2001; Wood and Chung, 2003). Sustained baiting, developed in the early 1970s (Fall, 1977), is still recommended for reducing rodent losses to rice-field rats, even when damage levels are low (Reissig *et al.*, 1985; Singleton and Petch, 1994; Hoque and Sanchez, 2008). The technique initially requires a continuous, low-level input of bait which is monitored and supplemented as rodenticide bait consumption increases during the crop season, and then terminated before harvest. Costs are, therefore, related to the actual risk of damage and the unnecessary use of rodenticide is avoided, and the approach has been even more profitable to farmers in areas susceptible to significant losses.

Pulsed baiting promotes the application of second-generation anticoagulant rodenticides at intervals designed to reduce the amounts of labour and bait material used. Because of the greater toxicity of second-generation anticoagulants, they are generally sold to farmers as end-use products rather than as concentrates. Acute rodenticides, such as zinc phosphide, can also be applied at intervals, but often require prebaiting or other tactics to achieve a similar effect and, in stable rat populations, bait shyness may become a problem. The interval between baiting pulses may be as short as 1 week (Dubock, 1982; Buckle *et al.*, 1984a), or as long as 6 months (Advani and Mathur, 1988), depending on the rodent problem and the control objectives. End-use products with pre-formulated bait entail substantially higher costs, because the transportation of products, particularly those originating offshore, includes shipment and distribution costs for inert bait base material. While rodenticide concentrates are preferable for farm use, pre-formulated baits may be safer, easier to handle and still cost-effective if used properly (Ahmed and Fiedler, 2002). For some rodent species that hoard food, the use of loose bait is preferable, as animals may move prepared baits without consuming them.

Chemical repellents or those derived from predator urines, capsaicin or other natural products are often suggested as having the potential to reduce rodent damage to crops, and considerable research effort has been engaged on this approach for many years (e.g. Mason *et al.*, 1996). Nevertheless, repellents have, as yet, found very limited practical application (Mason, 1997, 1998; Tobin *et al.*, 1997) and are a particular concern if consumable portions of food crops hold potentially irritating or toxic residues. Limited success has been found with repellents for seeds, seedlings or tree crops browsed or girdled by rodents (Mason, 1997; Ngowo *et al.*, 2005).

Non-chemical

Non-chemical methods can be used alone or integrated with rodenticide use when practical and cost-effective. Continuing research efforts are clearly needed so that effective rodent damage control is less dependent on the use of rodenticides as a primary method (Leirs *et al.*, 1999). However, the continuous availability of food (including crops), water (irrigation in dry seasons) and shelter (prolific vegetation) maintains rodent populations in and around tropical agricultural fields and often limits the apparent effectiveness of physical and biological approaches to controlling crop damage.

In some situations, predators have been shown to have an impact on pest populations (Newsome, 1990) but, more commonly, the presence of vertebrate predators in crop areas generally reflects the presence of pest rodents (Howard, 1967). Despite abundant prey populations when crops mature, and for fleeting periods after harvests, it appears that most potential rodent predators do not maintain functional populations on a permanent basis in monotypic agricultural fields (Fall, 1977; Tobin and Fall, 2005). Nonetheless, artificial increases in predation have been periodically promoted as a method of rodent control, the most well-known attempt being introductions of the mongoose (*Herpestes javanicus*) to sugarcane-producing areas in the tropics during the late 1800s. Although these introductions were not successful in reducing rodent damage, they had long-lasting and unfortunate impacts on ground-nesting birds and provided a continuing reservoir of wildlife rabies. The excellent cover provided by field crops and the long intervals when fields are fallow between crops preclude the effective establishment of predator populations in many crop areas. Nevertheless, this approach continues to be investigated. Recent efforts have included the provision of artificial raptor perches or nesting structures and attempts to increase predator abundance, but field trial data to establish the effectiveness of such measures in increasing crop yields are lacking or inconsistent (Howard *et al.*, 1985; Askham, 1990; Smal *et al.*, 1990; Chia *et al.*, 1995; Wood and Chung, 2003; Witmer *et al.*, 2008). Notwithstanding, locally active rodent predators in farming areas should be maintained, and control programmes should be designed to minimize impact on predators and other desirable wildlife.

Barriers or fences have been effective in local situations. Inchaurraga (1973) used sheet metal barriers in South American rice fields to obtain a 5 t ha^{-1} yield compared with only 2 t ha^{-1} in unprotected plots. Shumake *et al.* (1979) demonstrated that non-lethal electric barriers could stop rat damage to rice plots, with impressive yield increases, and interrupt the activity sinks that occur when rodents are killed in large numbers on small areas (Uhler, 1967; Ahmed and Fiedler, 2002). Barriers are commonly used to protect more valuable crops, such as seedbeds or research plots. Unfortunately, some methods are hazardous and have killed humans, livestock and other non-target species. Quick and Manaligod (1991) reported 11 human fatalities in one area of the Philippines resulting from the use of 220 V electric wires strung from main lines to protect rice fields. Research on barrier methods continues and may yet result in more broadly useful techniques.

Trapping is usually not practical if rodents are numerous, affected areas too large, traps costly or reinvasion rapid. If traps are used, the intensity of effort needs to be related to the numbers and activity of rodents and compared with the level of crop damage. Usually, trapping has proven to be so labour intensive that little benefit is achieved or efforts cannot be maintained because farmers lose interest when local rodent activity is low before crops are susceptible. Still, in some special situations, for example experimental fields of deepwater rice (Islam and Karim, 1995), trapping has been used effectively to manage rat damage.

Lam (1988) and Lam *et al.* (1990) combined simple drift fence barriers and traps to prevent invasions of Asian rice-field rats (*Rattus argentiventer*) into substantial areas of susceptible rice. At IRRI, Singleton and numerous colleagues have refined this approach and used it as a means to improve community-wide approaches to rodent capture for the protection of rice crops (IRRI, 1992; Singleton *et al.*, 1998, 1999c). More recent research has demonstrated applications in various rice production systems (dela Cruz *et al.*, 2003; Sudarmaji *et al.*, 2010).

Habitat manipulation appears to have more potential in temperate, urban areas than in tropical crops (Colvin, 1991), though for some tropical crops, changing certain portions of agricultural habitats could be beneficial, and this approach at least bears further evaluation (Whisson, 1996; Horskins *et al.*, 1998; White *et al.*, 1998; Jacob, 2008). Wood (1991) noticed two distinct cultural practices in Malaysian rice fields that could account for major differences in rice yield and rodent damage. Large northern paddies with smaller and fewer bunds provided fewer nesting sites and less weedy shelter for Asian rice-field rats than did southern paddies with larger, more numerous bunds. Wood speculated that modifying the bunds in the south might result in lower damage. Weeding within and adjacent to field crops can also reduce rodent cover and damage (Hoque and Olvida, 1986), a concept understood by farmers using very traditional crop production methods (Litsinger *et al.*, 1982).

Synchronous planting shortens the period that crops remain susceptible to damage and reduces the chance of early- or late-maturing fields becoming focal points of rodent activity. However, labour shortages during the brief transplanting and harvest periods (for example, Wood and Chung, 2003) and the progressive availability of water in areas that use gravity irrigation may preclude synchronous planting.

Control Programme Organization

In any rodent damage control effort there are three basic strategies to choose from: tolerance of the damage, management of the damage, or eradication of rodents. Tolerance is practised by both farmers and government officials. It is usually selected because of apathy, a lack of awareness of crop damage, unfamiliarity with other options, or because of religious, social or legal taboos against harming animals. Tolerance may be useful when control requires more effort and cost than simply accepting crop losses. Permanent or temporary eradication of rodents from crop areas is generally not practical or ecologically sound. Large-scale rodent-control campaigns have often been based on the false premise that rodent eradication from crop areas was possible.

The most practical strategy is the management of crop damage. Whether for a large commercial grower, a research farm or an individual farmer, a management strategy should determine a minimum amount of damage or loss that can be accepted (Fall, 1991). Drummond (1991) presented a four-part management concept consisting of: (i) an objective leading to (ii) a plan for implementing (iii) actions or activities that are subject to (iv) an evaluation to determine the level of success. The objective should not be to reduce rodent populations, but rather to reduce damage, increase yield or lower rodent-borne disease to some predetermined and acceptable level.

Two general approaches to organizing rodent damage control programmes have been used. The first, the area-wide or community-based approach, with its origins in the urban rodent-control programmes of temperate countries, is clearly difficult to organize and maintain for tropical field crop situations owing to small farm sizes and high human populations. Such programmes (frequently built around external donor assistance) tend to foster bureaucracies that are more responsive to the vagaries of local politics than to protection of crops. However, area-wide programmes can be effectively organized when governments have the authority to demand, or the influence to attract, farmer participation (Sumangil, 1991; Leung *et al.*, 1999; Sudarmaji *et al.*, 2010). Rural communities, farmer cooperatives or other farmer organizations often provide an existing framework within which rodent-control activities can be introduced and implemented. In some situations (plantation crops or large holdings), large-scale rodent-control programmes must be handled by one individual or organization. The pulsed-baiting method for rodenticide use, which relies on area-wide applications, has been used effectively in these latter situations (Buckle, 1988; Wood, 2001; Ahmed and Fiedler, 2002). Smaller quantities of rodenticide bait applied at more locations but at longer time intervals provide adequate protection with less effort than do sustained baiting or other farm-based programmes, but this technique loses some advantage when adjacent farms do not participate or when the immigration of rodents is rapid. When large-scale programmes are appropriate, careful attention to early warning and surveillance procedures, the timing of treatments in relation to crop susceptibility, full participation of the affected community and the monitoring of crop damage are essential elements for effectiveness. Singleton *et al.* (1999c) have investigated and refined similar tactics using trap-barrier systems.

The second approach places responsibility for rodent control with individual farmers. This requires that each farmer must obtain materials needed and carry out rodent control in his own fields. Extension workers may assist by providing specific information and recommendations, but government personnel need not become directly involved in rodent-control operations except during major population outbreaks. Individual responsibility is a relatively new approach in many tropical countries. Farmers who have relied on government programmes in the past are reluctant to take individual initiatives. This constraint will probably continue until methods and materials are developed that are widely available for individual use at appropriate times, until effective means are available to inform and train farmers, and until national governments and donor organizations cease to promote subsidized area-wide programmes. The development of such individual farmer approaches in the Philippines in the 1970s made rodent control in rice fields parallel to other Green Revolution technologies, such as: the use of certified seed, fertilizer and irrigation; insect, disease and weed control; and advanced cultural practices (Reissig *et al.*, 1985; Hoque and Sanchez, 2008).

Primary Rodent Pests

Seven genera of rodents are responsible for most crop damage in tropical situations and these have been identified for the specific attention of international donors (Drummond, 1978). These genera range over wide areas, with some overlapping of continents. Consequently, they have received the most attention by international and national research and development programmes, and have the most information available about effective control practices. Singleton *et al.* (2010a) and Witmer and Singleton (2010) have identified numerous other rodent species, less widely distributed, that may sometimes cause serious crop damage. In this chapter, our names follow those used by Wilson and Reeder (2005) in *Mammal Species of the World*, except when we mention older names (which we have tried to clarify) or quote directly from other authors (particularly in the References section). A number of rodent names have changed since we first wrote this chapter in 1994, and many authors continue to use old names or variants, thereby causing considerable confusion in the rodent-control literature.

In 1994, we constructed range maps for important species and genera based on distribution information reported in the 1993 edition of Wilson and Reeder. Here, we refer the reader to online range maps constructed by the Global Biodiversity Information Facility (http://www.gbif.org), a multinational organization headquartered in Copenhagen, Denmark, that compiles current information, including range maps, based on specimen holdings in major international museums.

Rattus spp. (rats)

The genus *Rattus* (see range map at http://www.gbif.org/species/2439223) ranges worldwide and includes about 56 species, although only a few have adverse impacts on man. These rodents typically are generalists, exhibiting broad food and habitat preferences. They are the most abundant mammal as well as the most economically important rodent present in many countries. The most familiar are the Norway rat (*R. norvegicus*, which is not a species of primary tropical concern; see range map at: http://www.gbif.org/species/2439261) and the roof rat (*R. rattus*, range map at: http://www.gbif.org/species/2439270), which cohabit with humans nearly everywhere. Occasionally, they have adapted to living in agricultural fields (for example in crops in Hawaii), but crop damage is usually ascribed to other, less commensal species. Some subspecies of *Rattus*, such as the Philippine rice-field rat (*R. r. mindanensis*, now *R. tanezumi*; see range map at: http://www.gbif.org/species/2439262), are true field pests and, even though they may be opportunistic commensals, they thrive in the absence of dwellings. Introduced commensal rodents have disrupted the biodiversity on many islands throughout the tropics (Atkinson, 1985; Chapter 18) and attempts to eradicate *Rattus*, even on small islands, have required massive, labour-intensive efforts (Moors, 1985; Howald *et al.*, 2007), and often considerable precedent efforts, to assure regulatory compliance in such projects (Pitt *et al.*, 2011).

In addition to *R. rattus* and *R. tanezumi*, other species (*R. argentiventer*, *R. exulans*, *R. nitidus*, *R. losea* and *R. tiomanicus*) are present in various parts of Asia and the Pacific Basin where they may damage rice, oil palm, coconut, maize and a wide variety of other crops (Williams, 1985; Hoque *et al.*, 1988; Chapter 3). *R. tiomanicus* has been a chronic pest of ripening oil palm fruit in Malaysia, where resistance to warfarin has required the use of second-generation anticoagulants in control operations. *R. r. diardii* (now *R. tanezumi*), previously known primarily as a commensal species, has more recently become common in some oil palm plantations that are far removed from dwellings (Wood and Chung, 1990; Wood, 2001). *R. villosissimus* periodically irrupts and causes extensive crop damage in Australia.

Since Wood (1971) realized that Malaysian rice yields could be experimentally increased threefold with rodenticide baiting during the crop period, equally dramatic results have been achieved in Indonesia and Philippine rice fields. The costs of control efforts can usually be economically justified if yield losses exceed 0.5% (Buckle *et al.*, 1984b), but without effective control, average losses from rodent damage in field crops are usually much higher. Research has identified rodenticide formulation, bait placement and the timing of bait applications as key factors that determine the effectiveness of crop damage control. Timing proved to be most important when two formulations of warfarin were compared for controlling *R. argentiventer* damage to Malaysian rice (Buckle *et al.*, 1980).

Baiting begun shortly after transplanting and continuing for at least 4–8 weeks was more effective than other baiting schedules tested. Research in Philippine rice fields on *R. r. mindanensis* (now *R. tanezumi*) and *R. argentiventer* showed that it was critical to begin baiting early in the crop cycle and to distribute bait points within paddies instead of at central locations on dykes (Fall, 1977) in order to reach all individuals and assure that the rats actually causing the damage can access bait. The technique has been widely used (Reissig *et al.*, 1985; Singleton and Petch, 1994; Hoque and Sanchez, 2008) and has been adapted to work effectively in other crops (Fiedler *et al.*, 1982).

Bandicota spp. (bandicoot rats)

Bandicoot rats (see range map at: http://www.gbif.org/species/2437726) are major rodent pests in the irrigated crop fields of India (Prakash and Mathur, 1988; Mathur, 1997), and also cause significant damage in Sri Lanka, Nepal, Myanmar, Bangladesh and Pakistan. Substantial amounts of the total yield in field crops can be cached in burrows by these rodents, which are also important storage pests.

Field studies in Bangladesh on the biology and behaviour of the lesser bandicoot rat (*B. bengalensis*), in combination with laboratory results, offered clues for a potential strategy to reduce damage in maturing wheat (Poché *et al.*, 1982). Results from damage surveys showed that wheat fields were not utilized by these rodents until the booting stage, after which rapid immigration, burrow formation and wheat damage were observed. A zinc phosphide bait cake developed in Pakistan (Smythe and Khan, 1980) was effective in small-scale field trials and in a large-scale demonstration in wheat fields. Using this technique, a successful national campaign was carried out in Bangladesh in 1983 and 1984 (Adhikarya and Posamentier, 1987). Despite the minimal cost, time and effort required by Bangladeshi wheat farmers, it is unclear if or how well the programme continued to function. Donor assistance, long ended, played a large initial role in motivating government officials and programme participants. Private industry did not continue the local manufacture of high-quality zinc phosphide bait cakes, thereby permitting other substandard or adulterated products to dominate the marketplace, and probably degrading farmer confidence (Bruggers *et al.*, 1995).

Mathur (1997) found treatments with bromadiolone, warfarin and zinc phosphide baits could control damage by the lesser bandicoot rat in rice, wheat, coconut, and cacao. Singla and Parshad (2010) used bromadiolone alone or zinc phosphide followed by bromadiolone to reduce damage significantly in sugarcane and adjoining wheat fields. An evaluation of an area-wide approach was initiated by Sultana and Jaeger (1992) to determine whether damage in both wet season rice and dry season wheat could be reduced by single rodenticide applications at the time of the year when rodent populations are most vulnerable, after the monsoon floods recede. Preliminary results indicated that this minimal treatment might reduce major crop damage and could be more easily managed by government agencies and farmers.

Arvicanthis niloticus (Nile rat, unstriped grass rat)

The Nile rat (see range map at: http://www.gbif.org/species/2438914) is the predominant rodent pest in field crops in eastern Africa and Egypt and is occasionally abundant in western Africa as well. Nile rats are herbivorous and normally consume grass seeds, leaves and shoots during daylight hours. They have a generally short lifespan; predation may help to limit rodent numbers except during population peaks which, in Senegal, occur about every 4 years (Poulet, 1985). Breeding and population density generally follow seasonal trends related to rainfall and vegetation, including crops (Fiedler, 1988a). During dry seasons, when regional populations decline dramatically, relative abundance may appear to increase as survivors concentrate in restricted areas of irrigated croplands or other suitable habitats and become highly visible to farmers.

Little information has been gathered to describe crop damage from or to develop effective control techniques for this species in agricultural areas. However, it is susceptible to 1% zinc phosphide on whole sorghum bait mixed with 1% vegetable oil (Suliman *et al.*, 1984), a formulation now used in Sudan. Greaves (1989) reported that anticoagulants mixed with wheat grains were effective in the field, but Taylor (1968) observed poor bait acceptance during an outbreak in Kenya, and suggested that natural vegetation may have been preferred over the cereal grain bait being used. Makundi *et al.* (1999) summarized past and current practices for controlling damage by this species and outlined a comprehensive integrated pest management (IPM) strategy for this and associated commensal and agricultural rodents causing preharvest and postharvest losses.

Mastomys spp. (multimammate rats)

These small rodents (see range map at: http://www.gbif.org/species/2438904) are the most important agricultural rodent pest in Africa. The severe crop damage they cause is a result of their omnivorous and opportunistic feeding behaviour, extraordinary reproductive capabilities and a propensity for close association with human settlements. Multimammate rats thrive in the presence of cultivation and readily enter homes, damage stored foods and spread disease.

Considerable effort has reduced, but not eliminated, the confusion in the systematics of *Mastomys* (Robbins and van der Straeten, 1989). Within this species complex, animals display one of three chromosome numbers, which differentiate *M. natalensis* in southern Africa and *M. huberti* in eastern, central and western Africa (both with 32 chromosomes) from *M. coucha* (36 chromosomes) and *M. erythroleucus* (38 chromosomes). All of these types are physically and behaviourally similar, and as pests, they are often treated as one problem.

Although multimammate rats have been involved in virtually every documented regional rodent outbreak in sub-Saharan Africa (Fiedler, 1988b), comparatively little research on the damage they cause or the development of control approaches has been published. Taylor (1968) recorded observations during a major outbreak in Kenya, including an attempt to control the field damage caused by multimammate rats, Nile rats and four-striped grass mice (*Rhabdomys pumilio*). Several other studies that evaluated rodenticide formulations for multimammate rats in the field or laboratory have produced no consensus as to what materials or techniques are suitable for crop damage control (Fiedler, 1988a). Myllymäki (1987) suggested that control efforts should focus on symptomatic treatment during critical damage periods, such as in sown maize or preharvest cotton fields, which would provide Tanzanian farmers with immediate visible results – an approach with a better chance of farmer acceptance.

Like many other African rodents, multimammate rats generally have predictable patterns of breeding and abundance that follow seasonal precipitation patterns (Fiedler, 1988a). Telford (1989) followed *Praomys natalensis* (now *M. natalensis*) population trends and the amount and duration of the two annual rainy seasons occurring in Morogoro, Tanzania, over a 4 year period. Leirs *et al.* (1990) showed that this pattern of bimodal rainfall could be used to predict population densities and potential damage in subsequent crop seasons. These research findings should facilitate the development of an appropriate management strategy for control efforts in Tanzania and other African countries with similar problems (Makundi *et al.*, 1999).

Meriones spp. (jirds)

Damage to field and plantation crops by jirds (see range map at: http://www.gbif.org/species/2437686) is a significant problem in North Africa (Bernard, 1977) and the Near East (Greaves, 1989). Only in India has there been any major effort to examine systematically tropical crop damage problems caused by this group of pests

(Prakash and Mathur, 1988; Mathur, 1997; Parshad, 1999). Damage by *M. hurrianae* populations, which can average ≥300 animals ha^{-1}, occurs in grain and tree crops, grasslands, vegetables and irrigation schemes.

Burrow treatments have been the most practical and useful technique for reducing damage. Only small amounts of bait are required and access to bait by non-target animals is restricted. Whole-grain pearl millet (*Pennisetum typhoides*) is very attractive to jirds, particularly when natural food is scarce. Their hoarding behaviour would probably make multiple-dose anticoagulant baits costly to use except in low-level maintenance control programmes. Nevertheless, the use of chlorophacinone and coumatetralyl, as well as the single-dose anticoagulant brodifacoum, each formulated in a pearl millet base, reduced active burrows by 83, 81, and 91%, respectively, after 10 days (Mathur and Prakash, 1984).

Strychnine (0.5% with mineral oil) and zinc phosphide (0.6–2.5%) on wheat grains have reportedly been successful when used in burrow applications. However, Bernard (1977) reported that tolerance to 0.5% strychnine in some populations required a change in concentration to 2.5% to achieve adequate toxicity. Such strychnine tolerance has also been found in pocket gophers, *Thomomys bottae* (Lee *et al*., 1990), and large differences in strychnine efficacy have been reported among three subspecies of the California ground squirrel, *Spermophilus beecheyi* (Howard *et al*., 1990), and in Richardson's ground squirrel, *Spermophilus richardsonii* (Proulx *et al*., 2010), suggesting the need to check rodenticide efficacy periodically or for use against new species.

Sigmodon spp. (cotton rats)

The distribution of cotton rats (see range map at: http://www.gbif.org/species/2438146) ranges from the southern USA, through Central America, to north-western South America. Although cotton rats occasionally burrow, these 100–200 g herbivorous rodents generally prefer grassy habitats that provide abundant vegetation for shelter, food and nesting. Cotton rats normally are active at night, using distinct runways to traverse a home range of about 0.1–0.5 ha. Breeding can be year round in the tropics, but peaks probably occur in favourable seasons. Population outbreaks occur occasionally over large areas, probably associated with favourable climatic conditions. Holler *et al*. (1981) noted a capability for the doubling of cotton rat populations in 1 month in Florida sugarcane fields. Cotton rats damage maize, sugarcane, rice, cotton and a variety of other field, garden and plantation crops (Espinoza and Rowe, 1979; Elias and Fall, 1988). However, they are less damaging to flooded rice as they remain at the drier edges of fields or along dykes. If populations are high, rapid and significant damage may occur when fields are drained before harvest.

Methods used for controlling damage by cotton rats include removing weeds in and around crop fields to reduce suitable habitat and increase exposure to predation. Rodenticides that are reported effective include the anticoagulants diphacinone (0.005%), brodifacoum (0.005%), pival (0.025%), warfarin (0.025% on maize/groundnut oil), coumatetralyl (0.0375%) and coumachlor (1% in a paraffin/maize meal block). In addition to anticoagulants, zinc phosphide, formulated with grain/vegetable oil or cubed sweet potato, and bromethalin have been used to reduce cotton rat numbers. Lefebvre *et al*. (1978) found that acceptance of 1.88% zinc phosphide formulated on oat groats or cracked maize was similar and that prebaiting did not increase acceptance.

Field evaluations of damage control procedures in Latin America have been very limited. In Mexico, Martinez-Palacios *et al*. (1978) used 0.05% warfarin with a grain-based bait in small bags selectively applied at a rate of 2 kg ha^{-1} over two 1600 ha mixed-crop areas to reduce cotton rat populations at about 50% of the cost of zinc phosphide baiting. They attributed this success to the use of maize oil as an attractant on the bags. Kverno *et al*. (1971) made similar observations in Nicaragua where cotton rat acceptance of non-oiled bags was poor. While rodenticide baiting for cotton rat control still appears to be commonly used by farmers in Latin America, particularly during population outbreaks, no research-based programme recommendations are apparent in the recent literature (Witmer and Singleton, 2010). An extensive summary (in English) of the Latin America rodent research literature had little original information on cotton rat control (Mitchell *et al.*, 1989), and plant protection personnel from the region have had limited participation in recent rodent-control conferences (ICRBM, 2006).

Other important rodent pests of tropical agriculture

Web-footed rats (*Holochilus* spp.) can be important rodent pests in South American sugarcane, rice and cotton (Elias and Fall, 1988; Castillo, 1990). Cartaya and Aguilera (1985) found that most of the damage to rice in Venezuela attributable to *Holochilus* occurred during the earlier vegetative growth stages and amounted to 0.9% of the biomass. These 105–255 g, nocturnal, mostly herbivorous rodents are adapted to aquatic environments, and have partial webbing between the toes on the hind feet. They construct nests and feeding platforms above water level in flooded fields. Anticoagulant rodenticides have been field tested, but only in limited areas and for short periods, using trap success or bait acceptance for evaluation.

Greaves (1989) cast doubt on the frequency of significant crop damage by *Tatera* and *Gerbillus* in the Near East, but elsewhere these gerbils are mentioned as important pests of dryland agriculture (Fiedler, 1988b; Prakash and Mathur, 1988). Govinda Raj and Srihari (1987) identified the reproductive patterns of gerbils (*T. indica*) in India and suggested that control operations should begin before the onset of the breeding season, which is associated with rainfall. Formulated with pearl millet, a preferred bait base, anticoagulant rodenticides reduced active burrows of this gerbil as well as those of a sympatric species, *M. hurrianae*, in crop fields. *Gerbillus* populations occasionally irrupt in Asia and in Africa and are sometimes involved in serious damage to planted seed (Witmer and Singleton, 2010).

Rodent Control, Crop Protection, Integrated Pest Management, Ecologically Based Pest Management and Decision Making

Rodent control describes the approaches used for: protecting crops, natural resources or rare species; preventing the spread of rodent-borne diseases; protecting structures and commodities from damage; reducing overabundant populations in managed areas; eradicating rodents from confined areas such as islands; or removing single individuals from pest situations. Rodent-control programmes are called by many names, some chosen to describe the purpose of the programme, some to describe the methodology, some to conceptualize the general approach, and some simply for purposes of marketing to users, funding agencies or the public. Often, several techniques need to be used in combination to achieve lasting results. Most recently, the processes of selecting management techniques in relation to ecological variables and constraints, applying them in a planned and systematic way, monitoring progress, evaluating results and providing feedback have been termed integrated pest management or IPM (Kogan, 1998) or ecologically based pest management (National Research Council, 1996). Singleton *et al.* (1999a) conceptualized this process as ecologically based rodent management (EBRM).

It is important to recognize that the ecological principles and the array of available techniques involved in all such programmes are similar and that a new name chosen for an effort does not necessarily mean new information or new techniques are being utilized. In the 1994 chapter, we discussed rodent-control programmes in terms of IPM, and we prefer to retain that usage. Smith and Calvert (1978) defined IPM as broad, ecologically based control systems that use and manipulate multiple plant protection tactics in an effective and coordinated way.

More complex definitions have been developed, but theirs remains broadly applicable to all plant pest situations, including those involving rodents. As many countries, international organizations and the donor-supported international agricultural research centres have incorporated IPM into laws, regulations or policies, and established various IPM coordinator positions, we share Kogan's (1998) lament that the invention of new names for a 40-year-old paradigm that has achieved universal recognition, even as an acronym, is non-productive. Minimal field research on the integration of methods and evaluation of programmes has been conducted.

Few practical IPM programmes are in routine use for rodent damage problems in field crops (Spragins, 2006). Smith (1970) recognized more than 40 years ago that chemical pesticides would continue to provide powerful tools in IPM programmes and that the hope for 'revolutionary' approaches to pest control should not be a basis for rejecting effective chemical techniques (e.g. IRRI, 1992). Although IPM, as well as EBRM, has increasingly been promoted as an 'alternative' to use of chemical pesticides, in fact, and in practice, pesticides that are effectively and selectively used remain an important component of most successful IPM programmes, particularly in the management of rodent damage to field crops (Buckle, 1988, 1999). Nonetheless, in every pest situation we have described there are many opportunities to improve the effectiveness, selectivity and environmental compatibility of rodent damage control programmes by developing, evaluating and using ecologically based integrative approaches.

The development of approaches to reduce or prevent crop damage by rodents presents some special problems that require careful consideration (Marsh, 1981; Fall, 1991; Singleton, 1994; Singleton *et al.*, 2003). While the general population dynamics of rodents and the principles for their application in IPM programmes are well known from studies conducted in temperate countries (Davis, 1972), few basic ecological data exist for common rodent pest species in tropical agriculture, though since 1994 the situation has improved substantially, particularly for the most important rodent species. Much of the new literature is well summarized by Singleton *et al.* (1999a, 2003), Stenseth *et al.* (2003), and Witmer and Singleton (2010). The rodent pest species are all highly responsive to changes in environmental conditions, making it essential to develop a thorough understanding of the specific ecological, phenological and climatic factors that influence rodent population behaviour in particular crop situations. This may be particularly important in the future, as climatic patterns change in particular areas. Because rodents may be relatively long lived compared with field crop cycles, have the capability for relatively long-range movements across different habitats, and can reproduce rapidly whenever adequate food and cover are available, most rodent damage problems must be studied and evaluated in farmers' fields rather than on small plots or experiment stations. The same rodents often damage a variety of crops in the same area, shifting from one field to another as crop cover develops or ripening progresses. Seasonal movements from crop fields to dwellings or storage structures are common for a number of problem species. In some cases, more broadly based integrated programmes addressing community problems may be more practical and sustainable than specific crop-oriented approaches (Chapter 14).

Programmes in Malaysia, Indonesia and the Philippines have introduced IPM concepts to rodent control. The sustained baiting method, developed in the Philippines in the early 1970s, contained a self-monitoring component in which bait consumption – a reflection of rodent activity within rice fields – was regularly checked, and the baiting regimen increased or decreased accordingly to minimize rodenticide use (Fall, 1982; Hoque and Sanchez, 2008). Modifications of the procedure using placebo baits have been used for monitoring rodent activity so that control can be initiated when necessary (Howard *et al.*, 1979; Howard, 1983). Based on the Rennison and Buckle (1988) surveillance procedure using rat-damaged rice hills, Buckle *et al*. (1984b, 1985) and Buckle (1988) established thresholds ranging from 15 to 25% damaged hills (equivalent to 1.8–3% cut tillers) for rice field treatment with rodenticides in Malaysia and Indonesia. Recommendations called for weekly baiting with anticoagulants during the rice tillering stage, and the use of tracking powder or fumigation during the maturing stages. Damage assessments at harvest were used to monitor the success of the management programme and identify where rodent control should be emphasized in the next crop season.

IPM programmes that are tailored to the smallest manageable unit that can be handled by a trained farmer or farm worker, with guidance from IPM extension specialists when necessary, probably present the best prospects to be self-sustaining. Such approaches are also more likely to be compatible with other farming and pest-management practices. The sustained baiting technique was designed for a single farmer to use effectively regardless of whether or not surrounding fields were being protected. This approach allowed rodent control to be included in the 'package' of new rice production technology being provided to select Philippine farmers (Fall, 1977). Individual farmer-based programmes place the emphasis on extension workers to provide information to farmers about rodent damage control methods and on market development to assure the availability of materials. Whether using physical control methods or rodenticides, the effects of intensive rodent control on small areas extend well beyond the limits of the individual farm or field, opening up the possibilities of extension strategies that focus on the fraction of progressive farmers most receptive to practising new approaches. In some situations, farm-based programmes may be the preferred approach to manage chronic rodent damage problems, whereas area-wide approaches, directed by specialists, may be appropriate for managing regional rodent population outbreaks, even though both approaches might involve the same crops, rodent species and control methods.

The limited availability of materials for rodent damage control in rural areas is a worldwide problem that must be addressed country by country, and area by area, for the development of self-sustaining and successful IPM programmes. Specific efforts will generally be required by public or private sector organizers, whether the materials needed for a particular programme are rodenticides, bait materials, traps, fencing or simply information. If markets for materials are undeveloped in rural areas, if distribution networks are too costly for the private sector to establish, or if the costs of providing chemical registration or other regulatory data are higher than the potential profit for private industry, then specific government involvement may be necessary. In the USA, the US Department of Agriculture is involved in the development, registration, manufacture and distribution of minor-use vertebrate pest management materials that are needed in IPM programmes for which no other sources are available.

Many of the techniques, materials and practices available for rodent damage control programmes have the potential for adversely affecting other wildlife and reducing biotic diversity. Although farmers cannot be expected to divert agricultural lands or suffer crop damage to maintain wildlife populations, one need only consider the impact of such desperate rodent-control practices as the burning or destroying of habitat adjacent to croplands, or the poisoning of irrigation water, to recognize that the utility and impacts of rodent-control operations need careful evaluation. If other wildlife species are determined to have a measurable role in reducing crop damage, practices to encourage increased activity of predatory mammals or birds around crop fields may be a useful part of an IPM programme. Even if 'natural controls' are not demonstrated as practical components of crop damage prevention, IPM programmes should be developed with the dual objectives of minimizing both crop damage and environmental effects.

An increasing number of countries are requiring that data on wildlife impacts be provided before the use of rodenticides is permitted in field crops. Most rodenticides are toxic to a variety of mammals and some birds, but toxicity data alone are an insufficient basis for regulatory decision making. Because few species of wildlife can live in the transient habitats provided by crop fields, wildlife exposure to rodenticides can often be limited by careful timing of treatments or by selective methods of application. When the costs of evaluating the wildlife impacts of pest management methods and materials outweigh the profitability of potential markets, governments may need to assist in gathering data to ensure that effective IPM programmes can be developed to replace the ineffective, hazardous or destructive practices that farmers may use when nothing else is available.

In any attempt to control crop damage, many small and large decisions must be made by each of the participants. Often, little evaluation of the outcome of these decisions is attempted and practices are simply adopted as routine. Ideally, IPM systems can help to provide feedbacks from the results of rodent damage control operations to those responsible for decision making, ranging from individual producers to government officials. Many constraints – technical, economic, ecological, cultural, religious and political – affect decisions about rodent damage control. It is important to recognize that much of the biological, chemical and ecological information about rodents, rodent damage problems and the effectiveness of techniques and materials has been obtained by researchers without reference to the practical constraints or specific management objectives of any particular crop damage situation. There is a continuing challenge for both producers and pest management specialists to make careful, informed choices in translating the available technical information into safe and effective operational IPM crop protection programmes. However, there is certainly enough biological and technical information about rodent damage control in hand to pursue the development of applied programmes more aggressively (Davis, 1972).

Discussion

Characteristics of successful rodent-control programmes

In 1994, we believed that some initial international support to a tropical country seemed to be prerequisite for progress in rodent control to occur. The Philippines, having one of the more successful national programmes, had major technical and financial assistance from the United Nations Food and Agriculture Organization (FAO), the German Agency for Technical Cooperation (Deutsche Gesellschaft für Technische Zusammenarbeit, or GTZ; now the German Agency for International Cooperation, Deutsche Gesellschaft für Internationale Zusammenarbeit, or GIZ), and the US Agency for International Development (USAID) over a 20 year period (Sumangil, 1991). Other organizations that have provided assistance to tropical rodent-control programmes are the United Nations World Health Organization (WHO), the UK Overseas Development Administration (ODA; now the Department for International Development, or DFID), the Danish International Development Agency (DANIDA), the Belgium Administration for Development Cooperation, the Swiss Directorate of Development Cooperation and Humanitarian Aid, the World Bank, the Asian Development Bank and the Australian Centre for International Agricultural Research (ACIAR). At various times in the past and present, the CGIAR-sponsored international agricultural research centres have actively supported rodent-control training or assistance programmes. Other organizations engaged in rodent-control projects on a smaller scale have included the Rockefeller Foundation, the Bill & Melinda Gates Foundation, CARE, the Catholic Relief Services and the Mennonite Central Committee. Sponsored projects in Asia, Africa, Latin America and the Caribbean have contributed valuable information on key rodent problems.

Clearly, the era of major donor assistance for rodent control to lesser developed countries has ended, and progress in actual control programme implementation on national or international scales has slowed or stopped. Despite this, a number of nationally supported research efforts have emerged, suggesting continuing progress can be expected (Singleton *et al.*, 1999a, 2003).

Measuring success

Measuring the success of rodent-control programmes has received little attention. Most managers have had no real obligation or responsibility to evaluate programmes or, if they did, lacked the skills and a budget to do so. In each situation where the application of IPM principles is being considered, specific surveillance and monitoring practices appropriate to the crop, rodent species and farming practices should be devised to provide the essential information about management effectiveness. The common practice of counting dead animals following poisoning programmes gives no indication of programme effectiveness for protecting crops because it ignores remaining or rapidly reinvading animals and provides no information about crop damage.

Two national programmes have been subjected to independent evaluation. Dizon (1978) interviewed managers, extension workers and farmers soon after a new rodent-control programme was introduced in the Philippines and found a substantial lack of knowledge among extension workers and farmers about the required materials and procedures. Despite this handicap, about 2% of farmers after 1 year and about 12% after 2 years had adopted all or portions of the new technique. The management information system developed and used by the Philippine Bureau of Plant Industry to track rodent-control efforts in relation to crop damage assessments (Sumangil, 1991) provided a mechanism to maintain a national overview during the initial efforts to implement new procedures for rodent damage control (Hoque and Sanchez, 2008; Singleton *et al.*, 2008).

Adhikarya and Posamentier (1987) evaluated rodent-control campaigns in Bangladesh, where considerable effort was expended on developing and testing extension methods designed to motivate farmers. As a result, an additional 5045 t of wheat were harvested in 1983, and in 1984 an additional 5208 t of wheat were realized. Bait costs for these campaigns averaged about 3–5% of the value of the increased production. The gains were probably larger because only wheat fields were evaluated, even though non-wheat crops were officially included in the 1984 campaign.

In addition, a number of countries with some tropical agricultural areas within their borders have engaged in both rodent research and control efforts. India, in particular, with diverse rodent damage problems across several climatic zones (Prakash, 1988; Parshad, 1999), has long maintained science-based, nationally coordinated rodent-control programmes with reporting and evaluation components.

Keys to success

Ecological understanding of crop damage problems

The full understanding of a rodent pest problem requires considerable time for studying rodent biology and behaviour under actual field conditions (Singleton *et al.*, 1999a). Beyond this important initial research phase, the monitoring of rodent reproduction and movements, population status and condition, and crop damage patterns, and relating these data to climate and vegetation over several seasons, can provide the basis for models to forecast with reasonable accuracy short- and long-term rodent population and changes in damage (Leirs *et al.*, 1996; Stenseth *et al.*, 2001). With appropriate quantitative techniques, sensitivity testing on individual components of a model can identify key factors contributing to crop damage and help to identify appropriate control strategies and methods for field evaluation (Benigno *et al.*, 1983).

Establishment of clear programme objectives

A control programme should have stated objectives that focus on effectively reducing damage to priority crops and increasing farm yields and income within a given area and period. In many cases, an 'area' can be an individual farm. With such a focus, a programme will be less likely to lose sight of its primary mission. Successful programmes have made extensive and creative efforts to inform farmers and rural populations about the purpose and potential benefits of effective rodent damage control.

Well-organized implementation efforts

A well-organized operational programme can reduce significant rodent damage. During the 1976 rodent outbreak in Sudan, all areas of the country (including the Gezira Scheme, an intensively irrigated agricultural production area of more than 930,000 ha located between the Blue and White Nile Rivers) were severely affected by rodent damage. A result of this outbreak was the establishment of a programme in the Gezira Scheme to research, conduct and monitor operational rodent control. Some 10 years later, during the 1986–1987 Sudan rodent outbreak, the only area in the country not seriously affected was within the Gezira Scheme, where the well-organized rodent-control programme had been continued. Not only were annual yields protected from chronic losses over several years, but severe damage during one of Sudan's worst rodent outbreaks was avoided (Fiedler, 1988a).

In too many situations, there is no organization until an outbreak or some other acute problem requires it. Hastily made decisions are then usually based on limited, earlier research or information from other situations, which may or may not apply (Ramsey and Wilson, 2000). Responsibilities for specific actions must be recognized from the highest levels of government to the individual farmer, or control programmes will be ineffective. For example, at national levels, health and agriculture officials may not agree on who is responsible for rodent control when both public health and agricultural production are at risk from overabundant rodent populations. At the farm level, farmers may delay action because they feel that the government will take responsibility for controlling rodents.

Providing technical information to programme participants

An informed public is more cooperative and more likely to participate in rodent damage control programmes (Rampaud and Richards, 1988), but questions remain about how to inform. In this sense, the problems of improving rodent damage control parallel those of other agricultural production technologies. Effective communication methods will vary with social and cultural traditions, which can pose some formidable constraints in rodent-control technology transfer. For example, Adhikarya and Posamentier (1987) tested various Bangladeshi extension materials for farmer acceptance and found that some symbols and pictures in those extension materials had to be eliminated or changed because of adverse meanings or implications previously unknown to them. IRRI in the Philippines developed various production and pest management guides (for example, Reissig *et al.*, 1985) and has periodically sponsored workshops and training sessions for farmers, extension technicians and research workers. Elsewhere, radio broadcasts have been used to inform farmers, and widely distributed posters have been used in control campaigns introducing new national programmes. The introduction of rodent-control information through schools and local markets, training sessions involving key farmers or farmer groups, and the selection of demonstration farms, are other approaches that may have value in some situations.

Reasons for slow progress

Sustained adoption of improved rodent damage control methods, even those that have been properly researched, developed, demonstrated and extended to farmers, has been low, although we believe substantial improvement has taken place since we studied the problem in 1994. Poor adoption is frequently blamed on costs of materials, limitations on labour, the unpredictable nature of crop damage, or the lack of information and appropriate materials at appropriate times in crop cycles. Subsistence farmers may have little incentive to control rodents or to increase crop yields until land is predictably available or markets for crops are developed. Without some type of credit programme, even progressive farmers may lack the money required for preharvest investments in crop protection materials, or they may be reluctant to borrow even when credit is available, sometimes because of a history of excessive or unpredictable losses of crops to pests, weather or other factors.

For the most part, farmers rely on their own experience and that of their neighbours in making decisions on adopting new technology. Substantial benefits in farmers' fields create awareness, but, as many programmes have learned, creating awareness is much easier to accomplish than motivating farmers to use new technology. Of course, from the farmer's standpoint, rodent damage is only one of many risk factors that can result in crop losses; similarly, crop protection is only one of many aspects of crop production that a farmer must manage (and finance) year after year. In many tropical agricultural situations, a conservative attitude by farmers in the adoption of and investment in new technology is to be expected. This expectation should be a part of programme development and planning.

Poor programme results can also be expected if the involvement of government and rapport with farmers are lacking. However, the involvement of governments should not result in farmer dependence, which can be a major hindrance to establishing rodent damage control as an ongoing crop protection effort. The time and effort involved in organizing and managing effective government rodent-control programmes is much more than most realize. A national programme in Taiwan took 6 months to prepare and 2 months to evaluate in addition to the actual control operation (Ku, 1984). The marketing of ineffective or adulterated rodent-control products (Bruggers *et al.*, 1995) may result in farmers avoiding the further use of similar materials, good or bad. Government involvement in the quality assurance and regulation of agricultural chemicals may help to prevent this lack of farmer confidence. Sometimes, the non-availability of, or lack of easy access to, markets for excess produce inhibit farmer efforts and investments to increase crop production. Increasing national crop yields may prove to take decades of change – in social attitudes, agricultural policies, farmer awareness and knowledge, and development of the necessary infrastructure and support systems in rural areas. Continued effort is needed to ensure that the development of technology and programmes for controlling rodent damage is coordinated and keeps pace with other efforts in agricultural development.

The need for dynamic rodent damage control programmes

International agency support for research, training, operations and coordination was an initial driving force in the development of many national programmes. The publication of the results of research and development activities related to rodent control has made much valuable information readily available, including crop damage estimates for several important rodent species (Witmer and Singleton, 2010). National priorities are influenced mostly by economic factors, and without convincing descriptions of the extent of losses, rodent control will be likely to remain a low priority (Richards, 1988). Programmes that have had more success than others have identified economic losses and used the results either to initiate other programmes or strengthen existing ones.

In many surveys, farmers in the tropics rank rodents among their most significant crop pests (for example: Litsinger *et al.*, 1982; Adesina *et al.*, 1994; Singleton *et al.*, 1999b; Tuan *et al.*, 2003; Makundi *et al.*, 2005). This view is often endorsed by government plant protection officials. However, vertebrate pests have more often been viewed either as too different to be considered in insect-oriented national crop protection programmes or, indeed, as unique and so also not suitable for consideration in such programmes. Rarely have rodent damage management programmes been included with other IPM efforts. National crop production/protection packages and recommendations could easily incorporate available information on rodent-control technology, thus allowing the strategies to achieve technology adoption to be developed and implemented in a coordinated manner so as to provide comprehensive information to farmers. We believe considerable progress has been made in this regard since we first began to investigate tropical rodent problems in the 1960s.

Rodent pest management is not a temporary problem. Changes in agricultural habitats, the introduction of new crop varieties and farming practices, the development of improved irrigation, greater annual crop production, the continued rapid growth of human populations and changing climatic patterns will all cause many ecological changes that affect rodent behaviour, population patterns and crop damage. If control methods and management programmes are dynamic enough to account for these changes, the successes achieved so far will be sustained and progress in rodent damage control can continue (Witmer and Singleton, 2010).

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14 Sociology and Communication of Rodent Management in Developing Countries

G.R. Singleton and R.J.B. Flor
International Rice Research Institute, Metro Manila, Philippines

Introduction

In 2010, approximately 925 million people in the world suffered from hunger (FAO 2010). Rodents compete with humans for food in urban, peri-urban and rural communities. In developing countries in particular, there is a great demand for effective rodent management because rodents cause staggering production losses (Singleton, 2003; Stenseth *et al*., 2003; John, 2014). In Asia alone, annual production losses to rodents of cereal crops have been documented to be 5–15% in most countries (Singleton and Petch, 1994; Singleton, 2003), with occasional outbreaks of rodent populations typically leading to losses of >50% for smallholder farmers (Singleton *et al*., 2010). If losses to rodents of food crops in agricultural landscapes were reduced by just 5%, then almost 280 million undernourished people could be fed for a year (Meerburg *et al*., 2009). This chapter will focus on sociological and communication approaches that have been applied to tackling the management of rodent pests in agricultural landscapes in developing countries.

While humans have been dealing with rodents throughout history, and different management strategies have been designed, a key learning is that there is no cure-all solution that would be effective in all ecosystems (Leirs, 2003). Moreover, once a management strategy has been developed, then economic, cultural and social issues often limit its efficacy and scale of adoption. This is particularly the case in developing countries, where smallholder farmers not only have limited income to fund rodent management practices, they also generally have only 0.5–2 ha to grow their cereal crops. The small area of cropland per family brings cultural and social issues to the fore whenever a management strategy relies on early action or synchronous adoption of agricultural practices (e.g. synchronous planting) or community actions. For example, the use of a community trap-barrier system (CTBS) to control the rice-field rat, *Rattus argentiventer*, in Vietnam and Indonesia (see Singleton *et al*., 1999a,b and Singleton *et al*., 2003 for details) requires communities to share the costs of construction and ongoing maintenance of the trap barrier. This led to the development of a sociological framework for the use of the CTBS based on the concept of common property resources, and also to the associated constraints and opportunities (Morin *et al*., 2003). Similarly, the development of pulse baiting campaigns using rodenticides (Hoque and Sanchez, 2008), or approaches based on ecologically based rodent management (EBRM) (Singleton *et al*., 1999b), also highlight the need for sustainable and practical management strategies to be location specific and to target particular pest species (Belmain *et al.*, 2008).

The human dimensions to rodent pest management have been long recognized. The work by Charles Elton and his team on rodent pests during World War II provided much needed intellectual rigour to rodent management. Crowcroft wrote a fascinating account of the history of 'Elton's ecologists' and when considering the period 1939–1943 he commented: 'After the war, the professional staff employed in pest control… carried on the wartime professionalism, both in research and applying it to practical problems. The greatest change was in recognizing the importance of the human element' (Crowcroft, 1991). By contrast, the involvement of anthropologists, sociologists and specialist communicators in developing and analysing rodent management approaches is a more recent phenomenon.

In developing countries, the high cost of rodenticides, their limited availability, the cross-border trade of illegal poisons, often with labels written in a foreign language, and the emergence of resistance to the cheaper anticoagulants, have all led to communities and governments urgently seeking cheap, effective and easy-to-use methods of management. Adding to the complexity of this situation is the diversity of rodent pest species that cause significant losses in these countries (see Singleton *et al.*, 2007 for review). Although chemical rodenticides are still often the fallback management option when rodent densities are high, in recent years there has been a greater emphasis on EBRM for early and sustained management of rodent pests. The interest in EBRM has grown rapidly in South-east Asia, China, Mexico, eastern Africa and southern Africa. Indeed, in some countries (e.g. Indonesia and Vietnam) the government has proclaimed that EBRM is the official ratified national approach to rodent pest management in agricultural landscapes (Palis *et al.*, 2004).

In recent years, EBRM has moved beyond the ecology and economics of reducing rodent populations to address the challenge of how to engage communities to work together and to conduct management actions early in the cropping season (Singleton *et al.*, 2010). The latter is a particular challenge because farmers are being requested to switch their mindset from being reactive to being proactive in their control activities, i.e. they are being encouraged to conduct control before they perceive rodent losses to their crops – a difficult concept if this requires a high investment of time and/or money. The progress has been sufficiently promising for Krebs (2010) to observe that social science knowledge has merged with EBRM principles to help communities implement management practices that minimize damage and promote higher productivity and the well-being of farmers. These developments have risen along with the need for communication campaigns to target communities rather than individual farmers with EBRM, and for these communities to be built on dynamic, multi-stakeholder partnerships (Palis *et al.*, 2011).

In this chapter, we will provide an overview of some of the important developments and contributions of sociology and 'development communication' to the management of rodent pests, particularly in the cereal agroecosystems of developing countries. We will review some of the sociological approaches and tools that have been adopted to facilitate the implementation and dissemination of rodent management. Then we will provide case studies to highlight how social science and communication campaigns have played an important role in our efforts to change the behaviour of smallholder farmers.

Beginnings of Sociological Approaches in Rodent Pest Management

The recognition that the science of sociology can significantly benefit crop protection programmes started more than 25 years ago. The promotion of sociological tools to capture what people think and do became common in insect pest management and in the control of crop diseases in the 1980s (Norton and Mumford, 1983; Reichelderfer and Bottrell, 1985). Rodent pest managers began to be influenced by problem-oriented approaches that emerged during that time (Norton, 1988). One of these approaches was farming systems research (FSR), which identifies client groups, diagnoses priority constraints within farming systems, and then considers these in priority setting and planning processes (Merrill-Sands, 1986). Another approach was Conway's (1987) agroecosystems analysis (AEA); in this, a description of key components and interactions within the agroecosystem is fed into analyses of constraints and opportunities and actions for pest management (Angkasith, 1999). These and other general approaches influenced rodent pest researchers to include sociological factors when developing strategies for management (Norton, 1988).

Approaches and tools in the human aspect of rodent management

In rodent pest management, sociological tools are used in two connected categories, problem definition and solution implementation. One approach developed for understanding the problems of rodent pest management is 'decision analysis' (Norton, 1988). This approach starts with the people who are going to make decisions on pest management by describing who they are, their interactions and the reasons behind these people doing what they do. Decision analysis also involves a decision model that looks at the pest problem itself, the available management options, the perceptions of the problem by the decision makers, and the objectives of the decision makers (Norton and Mumford, 1983). Redhead and Singleton (1988) adopted a decision-analysis framework to analyse how end users may respond to science-based management recommendations for the management of the impacts of house mouse, *Mus domesticus*, on wheat crops in southern Australia. Decision matrices provided a tool for the scientists to consider management options in the short and medium term in the context of the social, cultural and economic factors that influence the decisions of stakeholders at both a policy and a farm level. A payoff matrix is then used to assess the likely benefits to the end user (Norton, 1988).

Another approach described by Norton (1988) is an 'expert systems' analysis that systematically looks into decision making for pest management. The system is composed of IF–THEN rules that could be presented as a decision chart. It may also involve a matrix that simplifies these rules and structures the knowledge needed to inform which options are best chosen to be done. The expert system can be complemented with photographs and short videos to reinforce how to implement management options. This approach provided the basis for the development of MOUSER, a decision-support platform for managing mouse populations in the wheat fields of Australia, which is available to end users on a CD-ROM (Brown *et al.*, 2001). MOUSER also included a simple economic model that allowed farmers to input the current wheat price, the cost of management actions and the likely economic impacts of mouse populations.

However, it was another decade before a similar level of decision support was applied to rodent management in a developing country. Brown *et al.* (2011) combined a rice crop production model with population data collected over 4 years and data on the dynamics of rodent damage to rice crops (which allows for compensation by the crop to damage at different crop stages). They applied the resulting simulation model to an irrigated cropping system in the Mekong Delta in Vietnam to explore the optimal timing and intensity of rodent management for increasing yields of rice. The simulation model factored ecological and economic relations to come up with a framework that could help farmers make decisions on investing in rodent control. Simulation models can also factor the extent of an investment by a farmer into the recommended decision (Stenseth *et al.*, 2003). Similarly, bio-economic models have the potential to consider a social planning scheme that could help farmers to time their control actions to maximize effectiveness (Skonhoft *et al.*, 2006).

Aside from expert systems, an integrated management scheme for rice-growing communities was proposed by Buckle (1988). This scheme involved farmers in frequently monitoring the percentage of rice hills with rat damage to make decisions on the need for control action using rodenticides (Buckle, 1999).

The underlying theme with the approaches described in this section is that we need to integrate our ecological understanding of rodent pests with the social factors that influence the decisions and actions of local stakeholders (e.g. extension professionals, farmers). There has been impressive progress with the development of tools that aid the end users of research, particularly farmers, to make informed decisions on the timing, cost and likely impact of management actions, although few of these formal decision tools have gone beyond the prototype stage.

The challenge is to adapt these tools so that they meet the needs of target groups in specific agroecosystems. One approach that will facilitate this major step is action research, which pursues both knowledge and change goals, and usually involves interventions (Hart and Bond, 1995). It is important that these interventions are scientifically sound, replicated and at an appropriate scale to generate clear, evidence-based recommendations (Sinclair, 1991). The idea is to learn more in a context-specific and problem-focused manner to inform the actions or changes necessary to improve the situation. In the pest-management literature, this approach is more commonly termed adaptive management or active adaptive management (Walters and Holling, 1990; King *et al.*, 2003). In this 'learning by doing' process, researchers partner decision makers and other stakeholders to understand the system, identify effective actions, implement these actions and evaluate them as they proceed (Walters and Holling, 1990; Braysher, 1993).

Over the years, the sociological approaches developed for rodent pest management have evolved into more simple tools to enable pest managers to work with communities. Decision-analysis matrices, for example, have been simplified to focus on the key factors influencing decisions by farmers on which actions should be based (Fig. 14.1a,b). The factors include timing, who will do the action, where it will be done, and whether the action is feasible, affordable, and socially, politically and environmentally acceptable (Aplin *et al.*, 2003). After the different factors are considered, decision makers then prioritize in a participatory manner which action(s) are best.

Participatory tools

Rodent management in an agricultural context requires an effective set of sociological and communication skills. Rodent managers can draw on an array of structured interview techniques to conduct quantitative household surveys and qualitative participatory rural appraisals. These include key informant interviews, focus group discussions, and the development of cropping calendars and community resource maps. The tools to capture the human side of rodent pest management are derived from conceptual frameworks developed to aid decision making and needs assessment.

One contribution from sociology is the tool of *focus groups*. This is a facilitated group meeting in which community representatives come together to discuss and decide on a problem and its management (Marshall and Rosmann, 1999). The focus group can be a simple discussion to elicit various perspectives on a topic while allowing the community to get together and to make decisions on management. It can also be connected with other tools to help communities think and act on what they need.

One such tool is creating *community resource maps*. These provide a landscape view of a village and the associated croplands. The map is drawn by a group of participants. In the context of rodent management, the maps help the group think about where rodents are at key times of the year, and what access they have to various habitat types in and around the agricultural crops, village houses and other community resources (Aplin *et al.*, 2003). This approach often helps different community members to be more comfortable in a group discussion (Horne and Stur, 2003), and it triggers the community to think how

(a)

Action	% of farmers	Timing (When)	Who	Where	Feasible	Economic	Priority
Cleaning/ weeding	100	Land preparation, maximum tillering and booting	Individual	Edge of rice field and stone wall	Yes	Yes	1
Block burrows	100	Land preparation, maximum tillering and booting	Individual	Edge of rice field and stone wall	Yes	Yes	2
Scarecrows	90	Signs of rat damage, 3 months pre-planting	Individual	In rice field	Yes	Yes	3
Zinc phosphide poison	30	Planting and panicle initiation	Individual	Along dykes	No	Expensive and not effective	4
Insecticides	0	Before transplanting	Individual	In rice field	No	Not for rodents	Not considered
Protect snakes and lizards	Variable	All the time	Community	Landscape	Not known	Yes	Not decided

(b)

Fig. 14.1. (a) Sample decision-analysis matrix from Mountain Province, Philippines. (b) Discussion of the matrix with the community in Mountain Province, Philippines.

rodents use a landscape at a community level, and who is responsible for managing habitats where rodents aggregate when the crops are fallow, or breed when there are suitable resources available.

Another tool is the *seasonal cropping calendar*: a focus group produces a simple matrix on the timing of key environmental, agricultural and social events that occur throughout the year. Last, in a focus group, the community and pest managers may also use the tool of *problem cause diagrams*. This tool facilitates the process of communities breaking down their pest problem and thinking about the causes and the effects of such problems (Aplin *et al.*, 2003).

These various sociological tools set the stage for making decisions on technology options to manage a problem (Horne and Stur, 2003). However, in the case of rodent pests, the farmers often do not understand the basic life history of rodents, particularly the timing of the breeding season and the distances that rodents are likely to migrate. Once the farmers are informed of the basic breeding biology and habitat use of rodents, then the cropping calendars and resource maps that are compiled provide the basis to conduct a decision analysis on how, when and where rodents need to be controlled, and who needs to be involved in the control (see Fig. 14.1a,b).

Often, farmers in developing countries have developed ingenious methods to cull rodent populations, but they may apply them too late and act as individuals. The set of sociological tools helps the group to think through their current management actions with respect to the causes of the problem, and what they can do together as a community. The resource maps help them to highlight where the rats are at key times, such as before they disperse into newly planted crops, and before they breed. Farmer groups will frequently identify key source habitats for rodents, but then indicate that control is rarely conducted in those areas because it is 'common land'. A focus group discussion may provide the impetus for communities to decide on coordinated collective action against rodents in such common land. Together, the cropping calendars and the knowledge provided on the breeding ecology of the major pest species provide the context for determining when to conduct control. The participatory tools are simply tools. Effective facilitation will draw upon these tools to encourage the community members to decide on their own rodent-management strategy within the time and resources that they have available during a year.

There are other participatory tools that are also useful in rodent pest management. One tool that looks at major events and changes that have had an impact on the community in the recent past is the *historical calendar* (Aplin *et al.*, 2003). This triggers the community to consider longer term changes that may affect rodent populations, or why there are episodic irruptions of rodent populations (see Chapter 1). The key is to encourage the community to think of changes that they can modify (Horne and Stur, 2003), or to monitor for early signs of population irruptions. Historical calendars are best done in key informant or small group interviews.

The different participatory tools can also be used in participatory rural appraisals of rodent problems (von Maltitz *et al.*, 2003). The development of tools to quantify the knowledge, attitudes and practices (KAP) of farmers has been instrumental in progressing EBRM (Aplin *et al.*, 2003) and the tools also provide a platform to assess the impact and sustainability of management actions (see next section). Approaches geared towards integrated management with the use of rodenticides, such as the systems approach described by Richards (1986b), are linked to top-down implementation through an extension system or commercial network (Fiedler, 1985; Richards, 1986a). However, the nature of EBRM as a technology requires participatory methods to involve communities in problem assessment and development of solutions.

Other qualitative tools

Qualitative tools have been used in rodent pest management to obtain an understanding of human or social reality in communities. Social scientists and development practitioners often do *in-depth interviews* and *case studies* to obtain a picture of social conditions that are relevant to pest management (Morin *et al.*, 2003; Palis *et al.*, 2003, 2007; Le Anh Tuan *et al.*, 2010). The theoretical lenses used to document how people use their landscape, their behaviour towards managing rodent pests and their cultural mores concerning rodents underpin the way that social scientists examine the adaptive processes adopted by communities involved in pest management. These qualitative tools are employed to capture patterns in cultural traits such as the social organization and socio-economic relations in a community (McGee and Warms, 2004). For rodent pest management, this gives insight into the varying resources and capacities of different members of the community that may affect the actions chosen (Aplin *et al.*, 2003).

Other participatory tools include *wealth analysis*, which builds upon the community resource map, and interviews or small informal discussions to characterize the different social groups and the economic status of each group. *Social mapping* is another tool, used in a similar manner to define the different groups within the community and to identify differences such as in ethnicity or economic status. This helps to target the actions, if needed, for different groups, and to monitor the relative impacts of the pest management conducted by each group (Horne and Stur, 2003).

Quantitative tools

Although the participatory approach provides useful and direct ways for communities to voice their opinions and to plan for rodent management, it also has some limits. For example, the opinions gathered may not be a representative sample of the opinions within the community. To reduce the bias from participatory tools, structured interviews and surveys have been used to capture human elements in rodent management. A commonly used tool is the KAP survey (Table 14.1). A well-designed KAP survey stratifies the collection of data across households within a community on the basis of farm characteristics, knowledge and perceptions of rodents, and practices for rodent management. These household data provide a robust method to monitor quantitatively and to evaluate statistically changes that occur with time or following the implementation of an extension programme. Comparisons between villages adopting different methods of rodent management (e.g. traditional practices versus EBRM) provide an ability to triangulate the effectiveness of rodent management with and without new practices, and before and after the implementation of new practices. Simple input–output data can be included in the KAP surveys to provide an economic costs and benefits analysis.

Case Studies of Sociological Approaches in Developing Countries

The use of sociological approaches and tools in rodent pest management has become more common in the developing countries of Asia and eastern and southern Africa in recent years (Table 14.1).

Africa

In eastern Africa, the adoption of EBRM action research on the multimammate mouse, *Mastomys natalensis*, in maize cropping systems not only emphasized a strong ecological focus but also generated economic analyses to identify effective management strategies (Leirs *et al.*, 2003; Stenseth *et al.*, 2003). The modelling is linked to the expert-system approaches of the 1980s, except that in this case the economic computations are combined with ecological models to provide recommendations on which strategies would be most effective at what particular time (Norton, 1988; Leirs, 2003).

Participatory approaches and tools have provided a platform for action research to manage rodent pests in Africa (see Makundi and Massawe, 2011, for a review). One example is the Ecorat project, which concentrated on development of ecologically based rodent management in southern Africa (see http://www.nri.org/projects/ecorat/). The project was implemented from 2007 to 2009 in Namibia, Swaziland and Tanzania, and incorporated different sociological tools to work with communities on rodent pest management. Researchers and community members discussed their pest problems in regular community meetings. The biologists also provided updates on the biology of the key pest species and facilitated community projects for managing rodents in and around rural villages (see Belmain *et al.*, 2008).

Table 14.1. An overview of studies that have integrated sociological approaches and tools with rodent biology and management in developing countries.

Country and crop	Rodent species	Participatory tools/ approaches	Surveys[a]	Reference[b]
Africa				
Ethiopia, barley, tef, wheat, pulses	*Mastomys awashensis*, *Arvicanthis niloticus*		KAP survey	1
Namibia, Swaziland and Tanzania, maize	*Mastomys natalensis*, *Rattus rattus*	Focus groups, participatory research	KAP survey	2
Tanzania, maize	*M. natalensis*	Bio-economic models		3, 4
Asia				
Bangladesh, rice	*Bandicota bengalensis*	Adaptive management; focus groups; key informant interviews	KAP survey	5 6
Cambodia, rice	*Rattus argentiventer*, *R. rattus*	Adaptive management		7, 8
		Participatory research, focus groups		9, 10
China (Yunnan), rice, wheat, maize, potato, soybean, sugarcane			Economic survey	11
India, rice	*B. bengalensis*, *Bandicota indica*, *Tatera indica*, *Millardia meltada*, *Mus booduga*		KAP survey	12
Indonesia, rice	*R. argentiventer*	Multi-stakeholder partnerships	KAP survey	13, 14
				14
Laos, rice	*R. rattus*		KAP survey	15, 16
			Household survey	17
Myanmar, rice	*B. bengalensis*	Focus groups	KAP survey	18, 19
Philippines, rice, coconut	*Rattus tanezumi*	Focus groups		20
Vietnam, rice	*R. argentiventer*, *Rattus losea*	Multi-stakeholder partnership; focus groups; in depth interviews		21, 22, 23, 24, 25, 26
			Economic survey	21
			KAP survey	27, 28

[a]KAP survey: knowledge, attitudes and practices survey.
[b]References: 1, Yonas *et al.*, 2010; 2, Belmain *et al.*, 2008; 3, Stenseth *et al.*, 2003; 4, Leirs *et al.*, 2003; 5, Belmain *et al.*, 2007; 6, Ahaduzzaman and Sarker, 2010; 7, Russel *et al.*, 2003; 8, King *et al.*, 2003; 9, Frost and King, 2003; 10, Jahn *et al.*, 1999; 11, Dou *et al.*, 2003; 12, Sasikala and Neelanarayanan, 2008; 13, Sudarmaji *et al.*, 2003; 14, Sudarmaji *et al.*, 2010; 15, Brown and Khamphoukeo, 2010; 16, Brown and Khamphoukeo, 2007; 17, Promkerd *et al.*, 2008; 18, Brown *et al.*, 2008; 19, Htwe *et al.*, 2010; 20, Stuart *et al.*, 2010; 21, Palis *et al.*, 2003; 22, Palis *et al.*, 2004; 23, Palis *et al.*, 2005; 24, Palis *et al.*, 2007; 25, Morin *et al.*, 2003; 26, Le Anh Tuan *et al.*, 2010; 27, Nguyen Phu Tuan *et al.*, 2003; 28, Sang *et al.*, 2003.

Aside from focus groups, the project collected information through a KAP household survey to capture representative information on people's beliefs and attitudes towards rodents. A combination of ecological research and the learning from the sociological approaches aided the community in developing an intervention programme for their cereal crops that was appropriate to their socio-economic status.

In Ethiopia, Yonas *et al.* (2010) conducted a KAP survey to document the perspectives of farmers on rodent damage and management. The outputs from this study were to be combined with rodent ecological research with the aim of designing more effective interventions.

Asia

In Asia, the documented sociological approaches to rodent management vary considerably; they include adaptive management, the use of participatory tools, KAP studies, in-depth socio-economic assessments and the gathering of indigenous knowledge (Table 14.1).

KAP surveys have been commonly employed as a platform for rodent management in Asia. These include studies conducted in Indonesia (Sudarmaji *et al.*, 2003), in northern Vietnam (Nguyen Phu Tuan *et al.*, 2003; Palis *et al.*, 2011), in the Mekong Delta of Vietnam (Sang *et al.*, 2003), in Myanmar (Brown *et al.*, 2008), in India (Sasikala and Neelanarayanan, 2008), in Laos (Brown and Khamphoukeo, 2007, 2010; see Box 14.1) and in the Philippines (Stuart *et al.*, 2010). The studies were commonly part of projects that looked into EBRM in different communities, and all were conducted in rice-based agroecosystems.

A study in China also used a survey approach, but this focused on the economic factors affecting the adoption of integrated rodent management (IRM) in the highland areas of Yunnan Province, where up to 12 different species cause problems to agriculture (Dou *et al.*, 2003). The study documented benefit–cost ratios and other socio-economic factors essential in the use of IRM. These results were targeted towards informing both the government and the farmers in the decision-making process to use IRM.

Participatory adaptive management approaches for rodent management have also been reported in a few countries in Asia. These include a study on EBRM in eastern Bangladesh, which included the strong participation of rice farmers (Belmain *et al.*, 2007), and a Farmer-based Adaptive Rodent Management, Extension and Research System (FARMERS) project in Cambodia. The latter

Box 14.1. Case study on a knowledge, attitudes and practices (KAP) survey in Laos.

One tool commonly used in rodent management in South-east Asia is the knowledge, attitudes and practices (KAP) survey. The survey contains a set of questions that are asked during a formal interview of an individual farmer. The farmers are generally selected at random from within a village, and the sample size would depend on the size of the village. A typical interview would take 45 min.

The introduction of ecologically based rodent management (EBRM) to upland farming communities in Laos involved using this sociological tool to gather baseline information on the knowledge, attitudes and practices of farmers on rodent biology and management (Brown and Khamphoukeo 2007). After a year of participatory adaptive research, a post survey was done to compare changes before and after the implementation of EBRM (Brown and Khamphoukeo, 2010).

The baseline study documented that rodents are considered by upland farmers to be the most important pest of their rice crop, with an estimated mean yield loss of about 19% per crop. Trapping and rodenticide application were the most common control methods employed, but farmers used other methods as well.

The post survey found that while farmers still considered rodents to be the most significant pest, mean yield loss had been reduced to 12% in the project sites. Farmers did more trapping, along with other management methods, and some villages had banned the use of rodenticides. Although the project encouraged community action, most farmers still implemented management activities individually. The use of EBRM reduced the effort of each farmer in controlling rodents; however, there was an increase in the costs of control.

From the baseline and follow-up KAP surveys, pest managers gained insights on where to concentrate effort to further the implementation of EBRM in Laos. One key insight from the baseline was the need to promote community action and to develop supporting mechanisms from within communities. The follow-up survey found that a year was not enough to put these in place successfully. Further effort was recommended to encourage community action for rodent management.

also engaged communities in planning, implementation and evaluation activities (King *et al.*, 2003; Russel *et al.*, 2003). Sociological tools were also used to gather indigenous knowledge on rodent management (Frost and King, 2003).

One of the emphases in adaptive management is the linkage between what is being learned and the policy on rodent management at the local level (King *et al.*, 2003). In Indonesia, a multi-stakeholder partnership validated community-based rodent management at a village level. The research findings were disseminated by some of the government stakeholders to institutions involved in policy and extension, and led to the adoption of EBRM by the Government of Indonesia at a national level (Sudarmaji *et al.*, 2010). Partnerships with civil society groups, particularly non-government organizations (NGOs) have also provided positive outcomes for rodent management in Cambodia (Jahn *et al.*, 1999) and Vietnam (Le Anh Tuan *et al.*, 2010). The study by Le Anh Tuan *et al.* provided an interesting new dimension by examining the role of change agents in the participatory process to diffuse rodent management technologies.

Sociological studies in Vietnam have provided a solid foundation for understanding factors that contribute to the adoption or discontinuity of use of the CTBS (Morin *et al.*, 2003; Palis *et al.*, 2003, 2005). These studies included in-depth sociological examination of patterns of interaction and arrangements in the community for the management of a common property resource. Partial input–output surveys added deeper understanding to the economic viability of the technology from the perspective of the farmers involved.

An interesting development has been the progression from studies focused solely on the sociological element in pest management, to the integration of social and cultural information in understanding rodent management. This progression is nicely exemplified by contemporaneous studies of the sociopolitical and cultural effects of massive outbreaks of rodent populations in eastern India and Bangladesh, and in western Myanmar, following the masting of bamboo.

In Mizoram, India, Aplin and Lalsiamliana (2010) extensively described the context of rodent outbreaks, including historical events, local beliefs and the cultural background connecting such outbreaks with *mautam*, the masting of bamboo. In the Chittagong Hill Tracts of Bangladesh, Ahaduzzaman and Sarker (2010) and Belmain *et al.* (2010) explored the socio-economic and political situation of the affected communities. They described how researchers worked with farmers to understand and to document the problem, and they used focus group discussions and a survey to gather information from communities on the impact of the outbreaks. In Chin and Rakhine States in Myanmar, Htwe *et al.* (2010) conducted detailed structured discussions with communities affected by outbreaks to characterize their beliefs and the economic and social impacts. The removal of youths from school and the need for men to move large distances to find part-time employment and food for their families were two telling findings. These studies show how our understanding of rodent management has moved towards more integration of the social dimensions in understanding the social context, working with communities and looking into social impacts.

Mexico and South America

Integrated rodent management programmes that involved the use of sociological tools have been documented in South American countries. One case is the evaluation of an integrated programme for rodent control in Buenos Aires City, Argentina (Fernández *et al.*, 2007). As a complement to ecological studies, a household survey was implemented along with mapping using a geographical information system (GIS) of areas inhabited by people as well as other environments. The study provided the basis for management recommendations.

We are aware of a few other studies in Central and South America but there has been little documentation. Where ecological and social activities have been combined, the results have been promising but only on a local scale, e.g. the management of *Sigmodon* *arizonae* in maize fields in the state of Sinaloa in north Mexico (Beatriz Villa, personal communication).

Links with Human Health Issues in Rodent Management

Rodent pest problems are often seen as constraints to production, and much of the literature on sociological approaches focuses on the human element in relation to the management and adoption of management technologies in agricultural landscapes. The impact of rodents on the health of rural communities in developing countries is often ignored, despite the reality that rodent zoonoses can cause major impacts on the livelihoods of rural families (Singleton *et al.*, 2010). An investigation in Thailand examined a range of factors possibly associated with the risk that rice-field workers become infected with leptospirosis. Specific management practices such as the length of time farmers spent in flooded rice fields applying fertilizer, etc., or ploughing increased their risk of exposure to this parasitic disease (Tangkanakul *et al.*, 2000). Interestingly, the authors also reported that the frequency of potholes in the roads leading into a village increased the risk of infection.

In Laos in 2004, a survey assessed rodent infestation levels to identify factors that led to high densities of rodents in the city of Luang Prabang. The study, by Promkerd *et al.* (2008), documented human-mediated causes such as the structure of houses and gardens, or food storage and waste disposal. The authors identified potential rodent-borne diseases and stressed the need for appropriate management of rodents in urban areas.

Although limited, there are also reports on the social aspect of rodent meat as food for people. Nguyen Tri Khiem *et al.* (2003) traced six channels of rodent meat for human consumption in the Mekong Delta in Vietnam. The study documented the volume of rats traded for meat and the stakeholders involved in this trade. More importantly, it obtained data on health risks and protective measures for those who handle rats or who are near rat-meat processing points, highlighting the urgent need to assess the impacts of this trade on human health.

Where do we stand?

An impressive range of approaches and tools has been applied in rodent-management projects in many developing countries. Using one or a few of the tools available seems to be a basic part of the work done in rodent management, from problem assessment (including the politico-economic context) to working closely with communities to help them manage the pests effectively.

In 2003, some useful lessons from a sociological standpoint were summarized by Aplin *et al.* (2003). These included the short-term and longer term costs, constraints and benefits that have been documented in previous studies on rodent management. The lessons also include the need to consider risk, common property-resource concepts for community action, and social and institutional factors that are context specific. Learning from studies on social capital, stakeholder partnerships and their role in community action also provides important insights into pest management (Palis *et al.*, 2011).

From a sociological standpoint, these approaches and tools not only consider human elements in the process of communities acting on rodent management, but also allow communities to have a voice and to decide for themselves on a course of action. Since the 1980s, the approaches have changed in a way that has become more open for communities to take pest management further. Communities also decide on the direction that is most effective for them rather than on directions decided upon by outsiders or national programmes. These approaches consider history, differing access to resources and other cultural factors that the community needs to make explicit in the process of deciding upon and using pest-management strategies. Such community involvement is essential for the sustainable adoption of practices, particularly when the main pest species cause acute episodic problems rather than annual chronic problems.

At least in South-east Asia, there is a strong emphasis on participatory methods and adaptive management compared with the top-down expert recommendations that were common in the past. Also, multi-stakeholder partnerships have emerged as a solid platform for scaling out EBRM in Indonesia, Vietnam and eastern Africa.

Where next in applying sociology in rodent management? One area that has been largely ignored is the impact of rodent pests and the associated management strategies on gender roles. We need to add gender-disaggregated data to the quantitative surveys and, under some cultural situations, to have separate focus group discussions for males and females. Such an approach has been adopted in Bangladesh, and some subtle but important issues have emerged on perceptions and attitudes to management (Steve Belmain, personal communication; G.R. Singleton, unpublished data).

More emphasis also is needed on how to scale up the outputs of research to policy makers, and how to learn more about the most effective pathways for the diffusion (scaling out) of effective management strategies so that hundreds of thousands, rather than tens of thousands, of farmers are reached. This topic offers a good lead into the next section, because effective communication tools are required to strengthen the scaling up and out of the outputs and outcomes from the marriage between wildlife biology and sociology.

Communication and Rodent Management

In the developing world in the 1980s, it was recognized that information on rodent management, although perhaps not as organized as in other plant protection disciplines, had to be better communicated to increase its implementation and effectiveness (Fiedler, 1985; Posamentier, 1990; van Elsen and van de Fliert, 1990; Adhikarya, 1994). The need to communicate our understanding of the biology of the main rodent pest species in a local agricultural context, to create awareness of the problem and to move people into action are key concerns linking pest management with development communication. If the situation was as simple as extension specialists informing end users about the benefits and risks of new technologies, the efforts over the past 30–40 years would have sufficed (Priest, 2001). Moreover, in a developing country context, rodent pest management is primarily the domain of poor smallholder farmers rather than of the wealthier and more innovative farmers – who can easily be reached with new technologies (Posamentier, 1997). One of the biggest constraints is organizing a large number of farmers to manage pests in a cultivated area that is technically cost-effective to treat (Richards, 1986a,b). This is why effective multimedia channels have been promoted to reach different levels of targets, from extension workers to smallholder farmers (Adhikarya, 1994).

Communication for rodenticide-oriented management

At the time when rodenticide application was the basis of management strategies in most countries, a key challenge was to get hundreds or even thousands of farmers to act despite identified constraints in extension and the availability of chemical control (Sanchez and Benigno, 1985; Richards, 1986a,b). Concerns over human behaviour were identified as one of the practical problems in the implementation of rodenticides as a method of control (Sanchez and Benigno, 1985). An important challenge is the need to convince farmers to sustain applications of rodenticides even if they perceive a drop in rodent activity (Lam, 1990). Such challenges have led to the development of rodent-control campaigns in developing countries (Key and de la Piedra Constantino, 1992; Adhikarya, 1994).

Campaigns associated with rodenticide application largely depend on the integral involvement of extension workers and campaign personnel for not only technical advice, but also the assessment and monitoring of rodenticide treatments (Navarete, 1978; Key and de la Piedra Constantino, 1992). As commented by Posamentier (1997), some rodent-control programmes are managed by specialists whose key concern is the technical solution; and we need to move beyond that mindset. In the early 1990s in Thailand, a national campaign organized through the extension system provided rodenticides, while also promoting other management practices. The campaign covered 40 provinces in an agricultural area of almost 1 million ha (Boonsong *et al*., 1999).

In a field-rat control campaign in central Mexico, the best success was reported when the campaign focused on selected high-risk areas and then followed through with systematic monitoring. This provided sufficient time and flexibility for researchers to address management issues where and when they arose. The result was preventive rather than reactive management (Key and de la Piedra Constantino, 1992).

Other campaigns have tried to address the extension worker-dependence issue and to move rodent-management campaigns beyond simply sending out technical information. Campaigns in Bangladesh and Malaysia in the early 1980s had strategic extension campaign thrusts that were cost-effective without relying too heavily on extension workers (Adhikarya, 1994). A similar type of campaign was also implemented in Myanmar in 1987 (Posamentier and Nyunt, 1989; Posamentier 1994). These campaigns were the initial integration of mass communication into rodent management based around the use of rodenticides (Adhikarya, 1994; Posamentier, 1994).

In estate crops such as oil palm, it is primarily the private companies who implement rodenticide baiting. The scale of rodenticide use and the access to cash flow to pay for regular applications makes this a very different situation from those faced by smallholder farmers elsewhere in developing countries. We will not consider further the rodent-baiting campaigns in estate crops, but instead refer to Chapter 3 for further details.

Communication in integrated management

The use of mass-communication channels in rodent management developed hand in hand with the adoption of sociological methods such as KAP surveys and other participatory tools (Adhikarya, 1994; Posamentier, 1997). Communication components in joint programmes of rodent management included participatory assessment and planning, and the strategic choice of communication media and messages (Posamentier, 1997). Building on the integration of communication strategies and pest management, the principles and campaign methodologies were carried over to become an important platform for EBRM.

We briefly review a participatory campaign conducted in Luzon, Philippines, in 2006–2007, to highlight how EBRM has been promoted in a community rodent-control campaign, and how social tools also enabled the assessment of factors that influenced the sustainability of the key messages of the campaign. The campaign was undertaken in a similar manner to that described by Posamentier (1997). It was pre-empted by a needs analysis of information required on rodent biology and management by local government extension staff and smallholder rice farmers, along with research on the ecology and biology of the principal rodent pest species. Then campaign implementers, researchers, local officials and members of the community worked together to plan the campaign, *Boo! Boo! Rat! – Palay mo'y ligtas 24 h* (shoo away the rats – keep your rice secure all the time) (Zagado, 2008; Corales *et al*., 2010). Different media were used, targeting specific end users with specific EBRM messages. These media avenues included television coverage, a radio jingle, T-shirts, banners, posters attached to the back of public transport tricycles, and leaflets. Campaign monitoring through focus group discussions, a KAP survey and informal interviews were completed while field activities on rat management were implemented. The evaluation fed into the programme of activities helping the community and the researchers to work together effectively.

The scaling out of EBRM in Indonesia also exemplified a strategic communication approach led by one institution, the Indonesian Center for Rice Research (Sudarmaji *et al*., 2010). Written communication material, including brochures and posters, and a video, targeted visitors of the research institute, extension staff, farmers and policy makers. In addition, two web sites were developed with information on EBRM, targeted at extension specialists and policy makers. Adaptive research was conducted with farmers in their fields in different provinces. This was complemented by periodic national television and radio coverage that focused on key EBRM messages. In addition, EBRM principles were included in the curriculum of the leading provincial universities – an innovative strategy targeted at the next generation of research and extension staff.

Evaluation of communication campaigns

In Bangladesh and Malaysia, post-campaign evaluations indicated an increase in the number of farmers implementing control, a decline in rodent damage based on farmer feedback, and a reduction in the area damaged (Adhikarya, 1994).

In Thailand, a rodent-control campaign was evaluated by the Office of Agricultural Economics and was reported to be successful. Systematic and preventive rodent management was adopted by farmers. The management methods used were based on both acute and chronic rodenticides, and on physical methods of control (Boonsong *et al.*, 1999).

In the Philippines, the *Boo! Boo! Rat!* Campaign was evaluated a year after the campaign concluded. The sociological study examined the theory of change assumed in the campaign on EBRM and its effects on reaching smallholder farmers (Flor and Singleton, 2010). A high percentage of farmers was reached at the targeted villages through the strategic extension campaign. There was some spillover of the key messages to neighbouring villages. The study also documented which campaign activities and communication media were recalled by farmers, and which pathway of dissemination was most effective. The changes in the communities after the campaign in terms of both KAP and the mean yields obtained by farmers were captured (Flor and Singleton, 2011). A key finding was that the media campaign alone was not as effective as a campaign to support key community stakeholders. The support given by local leaders and extension staff to farmers for EBRM activities, along with a media campaign, disseminated EBRM effectively and resulted in positive economic benefits.

Conclusion

There has been strong progress since the mid-1990s in merging sociological approaches with rodent management and in using communications to promote management practices in developing countries. Anthropological and sociological tools have considerably advanced our understanding of why people do what they do in managing rodents. These studies have also highlighted that more needs to be done, particularly in understanding the key drivers in developing sustained community involvement by smallholder farmers in rodent management, and in developing more effective diffusion of management practices. KAP surveys have provided a standard tool for better understanding the current knowledge, attitudes and practices. However, there have only been two reports of studies with pre- and post-surveys that have been complemented by surveys in untreated villages to enable with and without comparisons (Brown and Khamphoukeo, 2010; Palis *et al.*, 2011). The Palis *et al.* (2011) study mentioned here is the first to quantify the factors that influence the diffusion of messages on integrated rodent management on a relatively large spatial scale. Such studies highlight the promise of opportunities to progress further social science and communications with effective rodent management in agricultural landscapes in developing countries.

One area where there has been little progress is the documenting of successful sociological and communication approaches to manage urban and peri-urban rodent problems in developing countries. An exception is the fascinating study on managing sanitary risks in squatter areas in the Cato Crest settlement in Durban, South Africa. This project produced exciting results: positive health benefits occurred after the development of a rodent-management campaign. The rodent population and disease studies were underpinned by the examination of anthropological factors relevant to rodent-borne disease transmission, and a socio-economic analysis of the squatter community. Combining the biological and sociological outputs then led to the development of an impressive community campaign (Taylor *et al.*, 2008). More studies of this nature are desperately needed.

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15 Ethics in Rodent Control

F.J.L. Smit
Dutch Society for the Protection of Animals, The Hague, The Netherlands

Introduction

Most vertebrate species across the Western world are relatively well protected from harm by appropriate legislation. Exceptions to this protection are made for several rodent species. The reason for this is that there is a general consensus that rodents such as house mice (*Mus musculus/domesticus*), Norway rats (*Rattus norvegicus*) and roof rats (*Rattus rattus*) are pests and may contaminate our food, damage property and transmit disease to humans, livestock and pets. Thus, these species are largely unprotected by law and can be killed in many ways (Chapters 5, 6 and 11). This is in sharp contrast to laboratory rats and mice which, in most countries, are covered by legislation that protects animals used in scientific experimentation. In this legislation, ethical principles for scientific procedures take a priority, meaning that research programmes have a legitimate purpose only when the harm inflicted (i.e. pain and suffering) outweighs the benefits. Furthermore, harm is minimized by the application of the three Rs, namely Replacement, Reduction and Refinement.

The three Rs principle is easily transferred to rodent pest control (Yeates, 2010) and would lead to a more humane approach in rodent pest management (Meerburg *et al.*, 2008). For example, replacement is applied through the use of preventive measures to reduce damage without having to kill animals (Chapter 5). A reduction of the number of animals to be killed is achieved by increasing hygiene and better housekeeping so that habitats are less prone to rodent infestation. Refinement may be delivered through the use of methods that kill animals quickly, thereby minimizing pain and suffering.

The application of an ethical approach is a reflective process in which one asks oneself 'do I do more good than harm if I act in this way?' It contains three important elements: facts, morally led principles and intuition/emotion (Ministerie van Economie, Landbouw en Innovatie, 2011). Ethics in pest control is often viewed as being difficult to deal with in practice, but is this really true? In order for all parties involved in pest control to act in a morally acceptable manner it is important that all of the facts are known. Knowing the facts will have an influence on morally led principles and intuitions. For example, clients for pest control in the food industry that have a mouse problem want to get rid of their problem quickly and cheaply. They know that mice can transfer disease and damage goods and property. They often think that avoiding mouse infestations through the use of preventive measures is too difficult to implement and expensive to achieve. They feel that the use of rodenticides offers the quickest and cheapest way to solve their problem (intuition). They also have a business to run (leading principle), and therefore cost-effectiveness will be decisive in their desired approach. This and other leading principles relevant to animals in our community are summarized in Table 15.1.

Customers for rodent-control services may not consider that biocidal products can cause problems to non-target species and may not be aware of the general consensus that rodenticides are not humane. The client should be aware of the following facts:

- Bad practice in the use of chemical products, such as rodenticides, can lead to secondary poisoning of non-target species (Chapter 16).
- Resistance against rodenticides in target species can occur, resulting in ineffectiveness (Chapter 9).
- Rodenticides should only be used at a minimum and in the European Union (EU) always in a proper manner according to EU and EU Member State law.
- Preventive measures can often reduce damage in a cost-effective way (Chapter 5).
- Rodents experience pain and suffering, are conscious of stress, and show forms of empathy (Chapter 7 and this chapter).
- There is a range of control methods to choose from that vary in their humaneness, and rodenticides are considered to be less humane than non-chemical methods, such as break-back traps.

This knowledge will lead to reduced demand for the less humane methods, such as many of the currently available biocides. In the following sections, the aim is to provide up-to-date and scientifically supported information on pain, stress, emotional status and empathy in rodents, as well as knowledge on the available models, from various sources, for implementing humane management strategies and assessing the humaneness of rodent-control methods. The concept of integrated pest management (IPM) is touched upon, as well as what is currently missing in that approach for the implementation of fully humane pest management strategies. Conclusions and some directions are provided to enable movement towards a more humane approach to rodent pest control.

Table 15.1. Leading moral principles relevant to animals in western communities.

Leading principle	Fate of animals depends on	Example
Business	Cost-efficiency and effectiveness	Cheaper (in the short run) inhumane pest control methods are favoured over expensive more humane methods.
Usefulness	Their use to humans	Animals that are of use to humans, such as pets, can be kept as companions, and livestock can be killed (usually humanely) for consumption. Animals that damage human goods are of no use and can, therefore, be killed.
Welfare	Whether their welfare can be guaranteed	Animals can be kept for pleasure, or for consumption, but only if their welfare is not compromised. Animals that can cause damage may be killed, but only in an effective and a humane way.
Bond	Bonding level with humans	Pets are more valuable than animals that are not. There is no bond with pest species and these can be killed.
Nature	Our duty to save endangered species	Animals of one species (i.e. rodents) can be killed to save another (e.g. endangered ground-nesting birds).

Pain and Empathy

Most legislation or guidelines relevant to rodent pest control state that the measures to be taken, or the products placed on the market, should not cause unnecessary pain and suffering in target animals. There is a general consensus that vertebrates consciously experience pain and distress (Bateson, 1991). The degree of pain and suffering inflicted on target rodents when using rodenticides, and other control measures, can be determined by looking at behavioural and physiological responses (see Chapter 7 and the section below on models for the assessment of humaneness).

In the past, discussion that considered pain in animals focused on whether animals experience pain consciously or whether they just show a withdrawal, or nociceptive, reflex response (i.e. moving away from the damaging object) to protect themselves. There are several steps to distinguish the so-called nociceptive reflex response from the capacity to feel pain. Physiologically, the species needs to have a suitable nervous system, including nociceptors. These are sensory receptors that detect and respond to damaging stimuli by sending a signal to the spinal cord and brain and causing the animal to display a reflex response. Another requirement for animals to experience pain is the presence of opioid receptors. These receptors reduce pain experienced by producing natural body opioids. Synthetic analgesics, such as morphine, should also induce a reduction in pain response. Further indicators of the experience of pain are: fluctuation in blood pressure; the production of stress hormones; changes in heart rate, respiratory rate and body temperature; and fluctuation in food and water consumption, resulting in changes in body weight as a response to noxious stimuli.

Behavioural evidence of consciousness of pain is present if animals show rapid avoidance learning and prolonged memory of the pain experience, and when trade-offs are found to exist between stimulus avoidance and other motivational requirements. A species will avoid a painful experience if no other positive stimulus awaits after the pain, but if the pain is not too severe, and going through this will result in a positive experience, such as a food reward, then an animal will endure pain. Being able to make these trade-off decisions indicates central processing – the ability to use complex information – and is suggestive of high cognitive abilities, including the ability to feel pain. Acute behavioural signs of pain are reluctance to move, abnormal posture, decreased appetite, vocalization and changes in facial expression.

Rodents show many physiological and behavioural responses that allow us to say with certainty that they consciously experience pain and stress. In the 1970s and 1980s, research showed the presence of nociception and opioid receptors in rodents (Quirion, 1984). Furthermore, rodents have similar brain structures to humans, and as shown by functional magnetic resonance imaging (fMRI), those areas activated in humans when experiencing pain are also activated in rats and mice when they are given a heat pain stimulus (Hess *et al.*, 2007; Heindl-Erdmann *et al.*, 2010).

When faced with stress or pain stimuli, rodents will respond behaviourally, and this altered behaviour is alleviated when analgesics are administered. A study conducted by Cobos *et al.* (2012) showed that mice with hind paw inflammation will significantly reduce their activity by making less use of activity wheels. When given anti-inflammatory and analgesic drugs, activity is restored, indicating that mice are conscious of their level of pain. Moreover, rats voluntarily change their preference for sugared water to water with analgesics when in pain (Colpaert *et al.*, 1980). This is a typical trade-off decision. They prefer sugar, but when they have learned that analgesics will alleviate pain, their preference shifts towards the less favoured drink containing analgesics.

From human facial expressions, one can read whether a person is in pain. Similarly, Langford *et al.* (2010a) were able to distinguish five facial features that indicated mice were undergoing unpleasant experiences. Those that were in pain had their eyes narrowed, bulged their noses and cheeks, had their ears in a flattened backward position along their body and the position of their whiskers was changed (Fig. 15.1).

Interestingly, pain-dependent behaviour in mice depends on a social context. The expression of pain behaviour increases in the presence of a familiar cage mate that is also in pain (Langford *et al*., 2006). In contrast, males reduce their pain behaviour when confronted with a strange healthy male. This makes sense in an evolutionary context: from familiar conspecifics, one might expect empathy and aid when experiencing and displaying distress and pain; however, showing these to strangers is dangerous in that it is a display of vulnerability, which might, for example, result in loss of territory. Langford *et al*. (2010b) further studied the social modulation of pain behaviour in mice and found evidence that animals in pain receive aid when they exhibit pain behaviour to familiar cage mates. Females visit same-sex cage mates in pain more frequently than those not in pain, or than those in pain but who are unfamiliar. What is more, the receiver of this approach, the mouse in pain, responds by showing reduced pain behaviour, suggesting that the close proximity of a familiar but pain-unaffected mouse may have analgesic properties.

Strangely, not all noxious stimuli result in easily measurable behavioural responses in rodents. Urban *et al*. (2011) exposed mice to chronic inflammatory pain or to two different types of neuropathic pain. They continuously measured activity and food and water intake. Only for the inflammatory pain did they observe reduced activity in mice in pain compared with controls, and this attenuated over time. Behavioural experiments were conducted to determine the animals' emotional state. The researchers tested the level of anxiety by conducting behavioural experiments. Time spent in the centre, or open, part of a maze area presumably indicates lack of anxiety, while the frequency of marble burying is indicative of anxiety. Few differences were found in behaviour between control and sick animals although, perhaps unexpectedly, in some test situations animals in pain appeared to be less anxious. From this study, it may be concluded that mice do not suffer much from chronic pain – but can we really conclude from pain experiments in which little or no behavioural responses are observed that animals do not suffer from pain? Perhaps current experimental paradigms do not always allow us to reveal fully the effect that pain has on animals; and they definitely do not fully address underlying affective states such as depression, which can be a consequence of pain (Flecknell *et al*., 2011).

The notion arose in the late 1940s that the environment in which rodents grow up affects their ability to learn and their

Fig. 15.1. Facial expressions of control mice and mice in either intermediate or strong pain. (From Langford *et al*., 2010a.)

emotional state (Hebb, 1949; Morgan, 1973). Those reared in an enriched environment differ in their learning capacities (Gill and Cain, 2011) and, depending on their genetic background, are less anxious than those reared in cages without enrichment (Chapillon *et al.*, 1999). The techniques used in research on the effect of the environment on cognition and pain perception have concentrated on tests such as open-field anxiety behaviour tests. More recently, workers have also tested whether emotional state can be determined in other ways. Brydges *et al.* (2011) tested whether positive cognitive biases occur when rats are raised in enriched environments (Fig. 15.2). Rats initially reared in dull environments, then placed in enriched environments, had a more optimistic view on life than those permanently raised in dull environments. In a Y-maze set-up, all rats were trained that when rough paper was present in the information chamber they could expect a high-value reward (chocolate) on the left site of the maze, while if the chamber contained smooth paper, they could expect a low-value (cereal) reward on the right site of the maze. When presented with an ambiguous cue – an intermediate piece of sandpaper – the rats reared in an enriched environment expected a high-value reward much more often. They were more optimistic than those raised in a dull environment. These subtle emotional states of rodents are not tested in standard pain-related behavioural research. Perhaps those animals that are brought into chronic pain, and those that do not show clear behavioural pain signs, would respond pessimistically in tests such as the ones

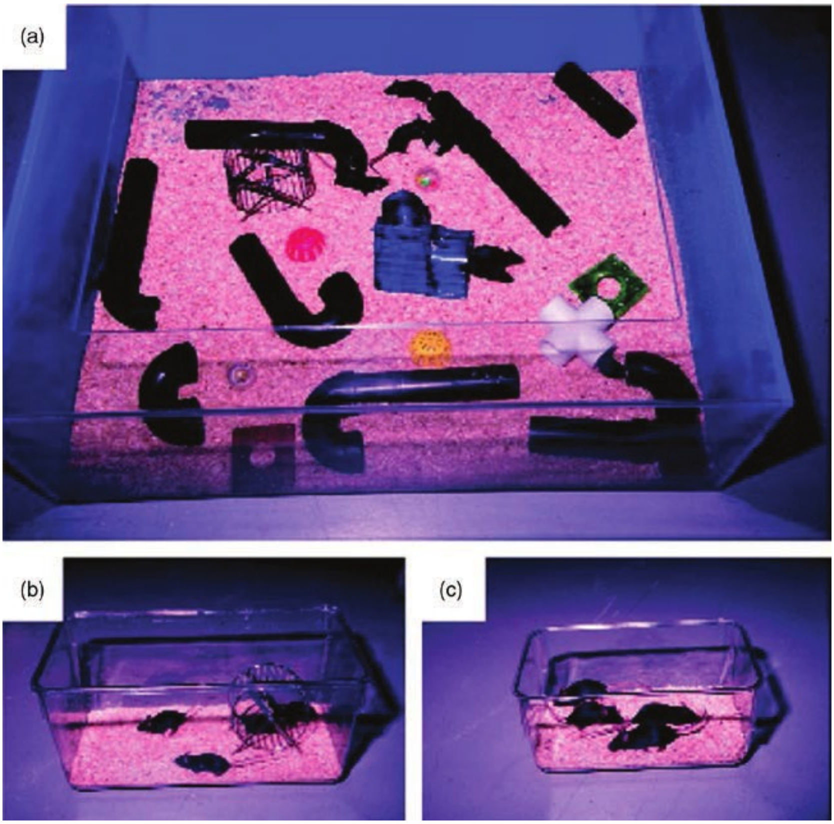

Fig. 15.2. Highly enriched (a), slightly enriched (b) and standard rodent housing cages (c). (From van Praag *et al.*, 1999.)

described above. More research into the effects of pain on the emotional state of rodents is necessary to answer these questions.

Humane Pest Management

As a result of an ongoing discussion about ethics and humaneness in vertebrate pest control, several papers and guidelines on humane pest control have appeared. Humane vertebrate pest control can be defined as: 'the development and selection of feasible control programmes and techniques that avoid or minimize pain, suffering and distress to target and non-target animals' (Humane Vertebrate Pest Control Working Group, 2004). There is consensus that the following principles should be at the forefront if a pest management programme is to be humane:

1. Legal and personal responsibility for humane outcome is established and communicated.
2. Legitimate purpose is established.
3. The benefits of the management programme outweigh the harms.
4. Effectiveness is monitored and control measures are adapted or cease if aims are not achieved.
5. The methods used seek to minimize harm (Humane Vertebrate Pest Control Working Group, 2004; Meerburg *et al.*, 2008; UFAW, 2009; Yeates, 2010).

By following a decision-making flow chart (Fig. 15.3), the operator (either a pest controller or a private person) ensures that control measures are based on ethical grounds and that *unnecessary* pain and suffering are avoided.

Legal and personal responsibility

Legislation on the use of mechanical rodent-control methods differs across Europe. Most countries have adopted a position that unnecessary pain and suffering should be avoided. Some have defined which type of traps can be used and in which location (indoors or outdoors). At the international level, the Agreement on International Humane Trapping Standards (AIHTS) has existed since 1997 between the EU, Canada, Russia and the USA (Harrop, 1998). Within the agreement, criteria for humaneness are established that must be fulfilled by killing and restraining traps, the species that may be taken are defined (including two rodents: the muskrat and the beaver) and the purpose for which they may be trapped (pest control, fur, skin and meat collection, conservation) is defined. Thus, the control of the house mouse and of Norway and roof rats does not need to comply with these standards. As a result of the AIHTS, international standards for testing killing-trap systems, ISO 10990-4 and ISO 10990-5 (ISO, 1999a,b), came into practice, but these have not yet been adopted into European legislation. Initially, the intention of these ISO standards was to establish humane trapping standards. However, no consensus was reached on whether the current AIHTS criteria can be considered humane, and so the term humane was removed from the title of the ISO standards. The debate continues.

The European Commission (EC) proposed standards in 2005, but the European Parliament suspected that they would not lead to humane trapping and demanded further research. When current wildlife standards in which kill traps are considered humane if animals are rendered unconscious within 60–180 s are compared with killing procedures for farmed animals in which unconsciousness is reached within a few seconds, it is indeed questionable whether the former timespan can be considered humane. Besides, many of the traps currently used do not comply with those standards (Iossa *et al.*, 2007).

The European Biocidal Products Directive (EU, 1998) prescribes that, for rodenticides to be placed on the market, they should not cause unnecessary pain or suffering. Unfortunately, the EU does not define what unnecessary pain or suffering is and so current protocols cannot test whether a biocidal product does or does not comply with this requirement. In 2013, this Directive was replaced by the Biocidal Products Regulation (EU, 2012), and Member States

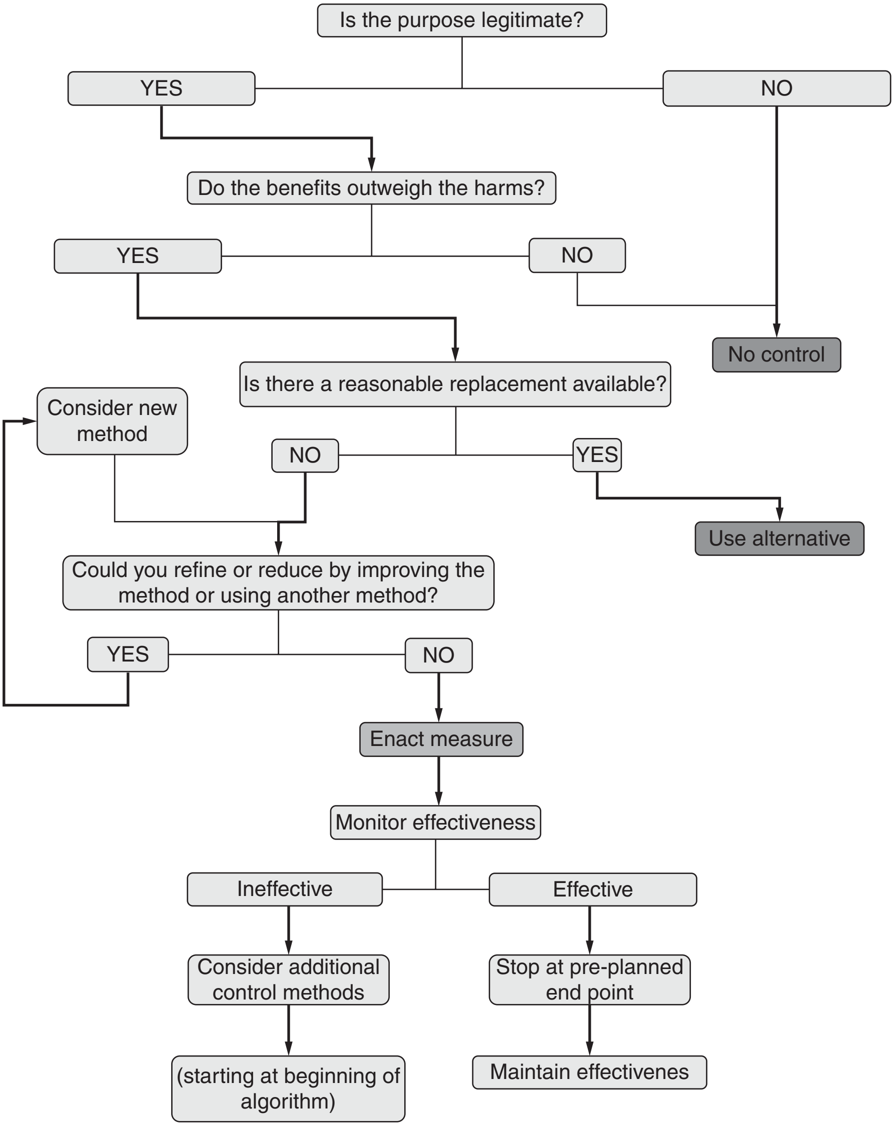

Fig. 15.3. General ethical decision-making flow chart to ensure humane pest management. (From Yeates, 2010.)

are obliged to implement this legislation directly. The Regulation, similar to its preceding Directive, aims to reduce the use of biocidal products. It states: 'Biocidal products shall be used properly'. Proper use includes: 'the rational application of a combination of physical, biological, chemical or other measures as appropriate, whereby the use of biocidal products is limited to the minimum necessary'. Biocidal products (i.e. rodenticides) have a far higher impact on animal welfare than, for example, break-back traps, because many more animals are killed by them and it takes a much longer time period for animals to die. Therefore, as this legislation is implemented among Member States, vertebrate pest control should become more humane across Europe. It is to be hoped that the precedents set in Europe will have far-reaching effects.

A range of information is needed by those who conduct rodent pest control if they are to operate as humanely as possible (RSPCA Australia, 2010; Yeates, 2010). This includes knowledge of legal requirements, measures for the prevention of rodent infestation, ethics, humane vertebrate pest control, integrated pest management, best practice for each control method, and which models of break-back traps, live traps and other equipment are of good quality and do not cause unnecessary harm to the animals. Pest controllers need to be educated, not only in these aspects, but also in how to transfer their knowledge to their clients in order to explain their legal obligations with regard to humane rodent control. On their part, clients have a responsibility to not only demand a pest control operation based on business-led principles, but also one that shows due regard to the environment and the principles of animal welfare. These principles are at the forefront of current EU legislation, and implementing them will result in legally correct and morally acceptable pest control.

Legitimate purpose

There is variation in the attitude of people and their underlying principles towards animals (Table 15.1), but there is also certain knowledge that all vertebrate animals feel pain and can suffer. As a result, it is necessary to set legitimate purposes for rodent pest control in legislation, just as is done for other human activities with potential to cause pain and suffering to vertebrates. Legitimate purposes may be considered to be, among other circumstances, when there is a risk of transfer of disease from rodents to humans and their companion and domesticated animals, and when there is a threat to food security or to biodiversity; but, for example, not merely to protect aesthetic appearance, such as a neat lawn, or to protect animals reared as game (Yeates, 2010). Legitimacy not only involves purpose, but is also closely tied to other components in the flow chart (Fig. 15.3). Rodent control has no legitimate purpose if the benefits of the control action do not outweigh the harms, and methods are used that cause high levels of suffering to target animals, especially if alternative, effective and more humane methods are available. Nor is control action legitimate if it is ineffectual, even if the control purpose itself is legitimate.

Benefits outweigh harms

For each pest control scenario, it is important that the potential costs of control actions are set against the anticipated benefits. Costs should not only involve financial aspects, but also the potential to cause harm to target and non-target animals (e.g. secondary poisoning, by-catch), the wider environment, future pest control (e.g. resistance development, see Chapter 9) and biodiversity, such as the risk that introduced predators may harm native animals (Yeates, 2010).

Benefits and aims must be clearly identified so that they can be maximized and any anticipated harms minimized (RSPCA Australia, 2010). Sometimes, the objective of rodent control is merely to reduce the impact of the pest, and this is commonly the case in agriculture. At other times, it is necessary to prevent any impact of the pest by its complete removal. An instance is the case of a predator rodent pest; can the predator be translocated without any harm to itself or to its prey animal, or is it necessary to eradicate the pest species? Which action will achieve the aim? For example, the complete eradication of rodents to protect endangered wildlife can be undertaken and achieved on oceanic islands, and the aim of the exercise effectively delivered (Lock, 2006; Chapter 18). In cases such as this, the benefits outweigh the harms. However, in mainland situations, clear boundaries need to be set. If a species is endangered, perhaps due to a combination of habitat loss and predation, it may be legitimate temporarily to control the predator species, but only if serious efforts to restore habitat quality and quantity are also made. Thus, a clear and deliverable end point should be in place. It is not possible to eradicate predators in most mainland scenarios because of the potential for recolonization (Chapter 18).

Therefore, if no efforts are made to make the endangered species more robust against predation, the control action would need to be in place indefinitely. In that case, the benefits of the programme will probably not outweigh the harms.

In all control programmes, it is important to monitor effectiveness, and if necessary to change the control strategy if it is not effective, or to abandon the programme completely if it is unlikely that its aims will be achieved using other acceptable methods (RSPCA Australia, 2010; Yeates, 2010).

Methods used minimize harm

If a control programme is both legitimate in purpose and in terms of its benefits outweighing the costs, the next step is to evaluate which methods can be used effectively while ensuring that harm to target (and non-target) animals is minimized. In order to make an evidence-based evaluation of this, the Australian Government constructed a model for assessing the relative humaneness of pest control methods (Sharp and Saunders, 2008). The model uses as a starting point the five freedoms of animal welfare (Brambell Committee, 1965; Farm Animal Welfare Council, 2013) to which farmed animals are considered to have a right. These rights comprise freedom: (i) from hunger and thirst; (ii) from discomfort; (iii) from pain, injury or disease; (iv) to express normal behaviour; and (v) from fear and distress. A two-part assessment process (A and B) is used.

Part A examines the impact of a control method on overall welfare and the duration of this impact. This is derived from the laboratory animal studies of Mellor (2004), Mellor and Reid (1994), Mellor and Stafford (2001), Mellor and Littin (2004) and Mellor *et al.* (2005), and uses five domains corresponding to the five freedoms of animal welfare (Fig. 15.4). A five-point scoring system is used for each domain. The control method under consideration receives a 'no', 'mild', 'moderate', 'severe' or 'extreme' impact score in each domain, and from this an average domain score is obtained. The duration of the impact is also determined ('immediate to seconds', 'minutes', 'hours', 'days' and 'weeks') to get an overall welfare score for Part A.

Part B examines the effects of the killing method on welfare by evaluating the intensity of suffering ('no', 'mild', 'moderate', 'severe' or 'extreme') and the duration of suffering caused by the technique ('immediate to seconds', 'minutes', 'hours', 'days'

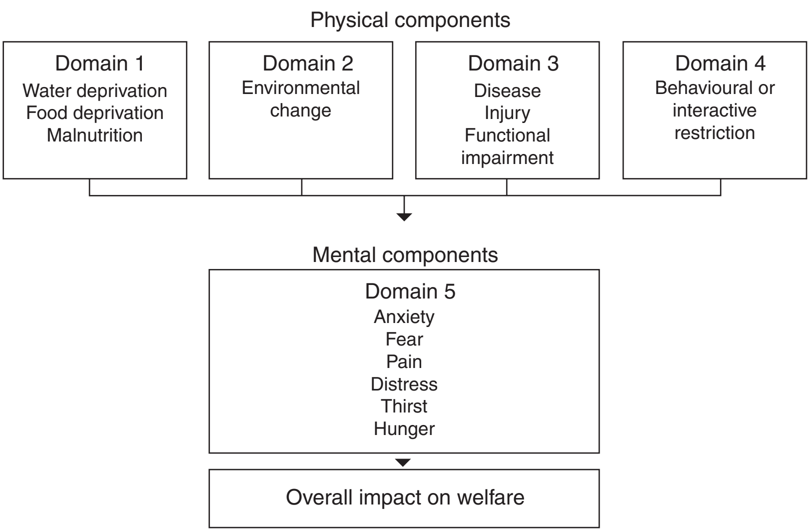

Fig. 15.4. The five domains of potential welfare impact (based on the 'five freedoms of animal welfare') divided broadly into their physical and mental components. (Modified from Mellor, 2004.)

and 'weeks'). This is derived from a vertebrate pest control model developed by Broom (1999). Part B only applies to lethal methods, while Part A is applicable to both lethal and non-lethal methods.

The Sharp and Saunders (2008) two-part humaneness assessment is applicable to control strategies with two phases. For example, a mouse can first be caught on a glue board and, if best practice guidelines are followed and boards are checked regularly, is subsequently killed by neck dislocation. The overall welfare impact before death is high (Part A), but the mode of death (Part B) is quick and may involve less suffering than the mode of death that is involved when using some rodenticides. In contrast, the overall welfare impact of rodenticides is scored very low in the Australian Government scheme when they are compared with glue boards (an impact of 1 versus 6, Fig. 15.5).

Interestingly, the New Zealand Government adapted the Sharpe and Saunders model, but, for brodifacoum (a second-generation anticoagulant), scored only the first stage of the assessment (Ministry of Agriculture and Forestry, 2010). In this way, they concluded that this rodenticide, and by implication other anticoagulants with the same mode of action, had a very high impact on welfare and is not considered to be humane.

When constructing Australian relative humaneness matrixes (Fig. 15.5), data from the scientific literature and expert opinion were used to score each of the five domains and the overall welfare impact in Part A, and to establish the degree of suffering caused by the mode of death in Part B. Several papers give insight into the level of pain and stress experienced by different rodent-control methods (see references in Yeates, 2010). For example, Mason and Littin (2003) reviewed conventional rodenticides, fumigants, traps, cellulose-based rodenticides, deterrence and proofing. The authors concluded that deterring and proofing, the use of well-designed and skilfully operated break-back traps, electrocution traps, cyanide gas and the conventional rodenticide alphachloralose are relatively humane methods for controlling rodents.

Clearly, if legislation differs between countries as it does currently in Europe, each country should make a similar assessment of humaneness for all rodent-control methods approved for use. Besides rodenticides, such assessments should also include non-lethal, though potentially effective, methods such as proofing and improved housekeeping/hygiene. It is important to realize that the impact on welfare of different control methods depends on whether they are operated under the conditions of best practice or not. For example, if a live trap is set with food and water, and it is checked regularly, its impact on welfare will be mild rather than extreme for Domain 1, and this will also reduce its impact on the mental component, Domain 5 (see Fig. 15.4). Therefore, for each method, it is important both to have clear best practice guidance and to ensure that those applying the method should use best practice (RSPCA Australia, 2010). Furthermore, break-back traps vary in quality and hence also in humaneness. Some brands do not have the strength to kill an animal quickly (Mason and Littin, 2003). Guiding devices leading the mouse or rat head first into a break-back trap will reduce the chance that the animal gets caught in the trap by an extremity, such as the leg or tail, which would lead to a slow death.

One mode of death that is controversial, and one that is slowing down the adoption of European trapping legislation, is drowning. Muskrats cause damage to dykes and waterways, so they are caught and killed in submerged live traps. Consequently, when muskrats are captured, the mode of death is drowning. If international trapping standards were adopted in EU legislation, submerged live traps would not comply with them because it takes too long for trapped animals to become unconscious. The question the European Parliament posed here is whether the conscious period before death is stressful for the muskrat, so the EC commissioned research on the subject; it was evident from the results that animals experience a high level of stress, based on both their behaviour (trying to chew their way out of the trap) and their stress hormone levels. What is more, on

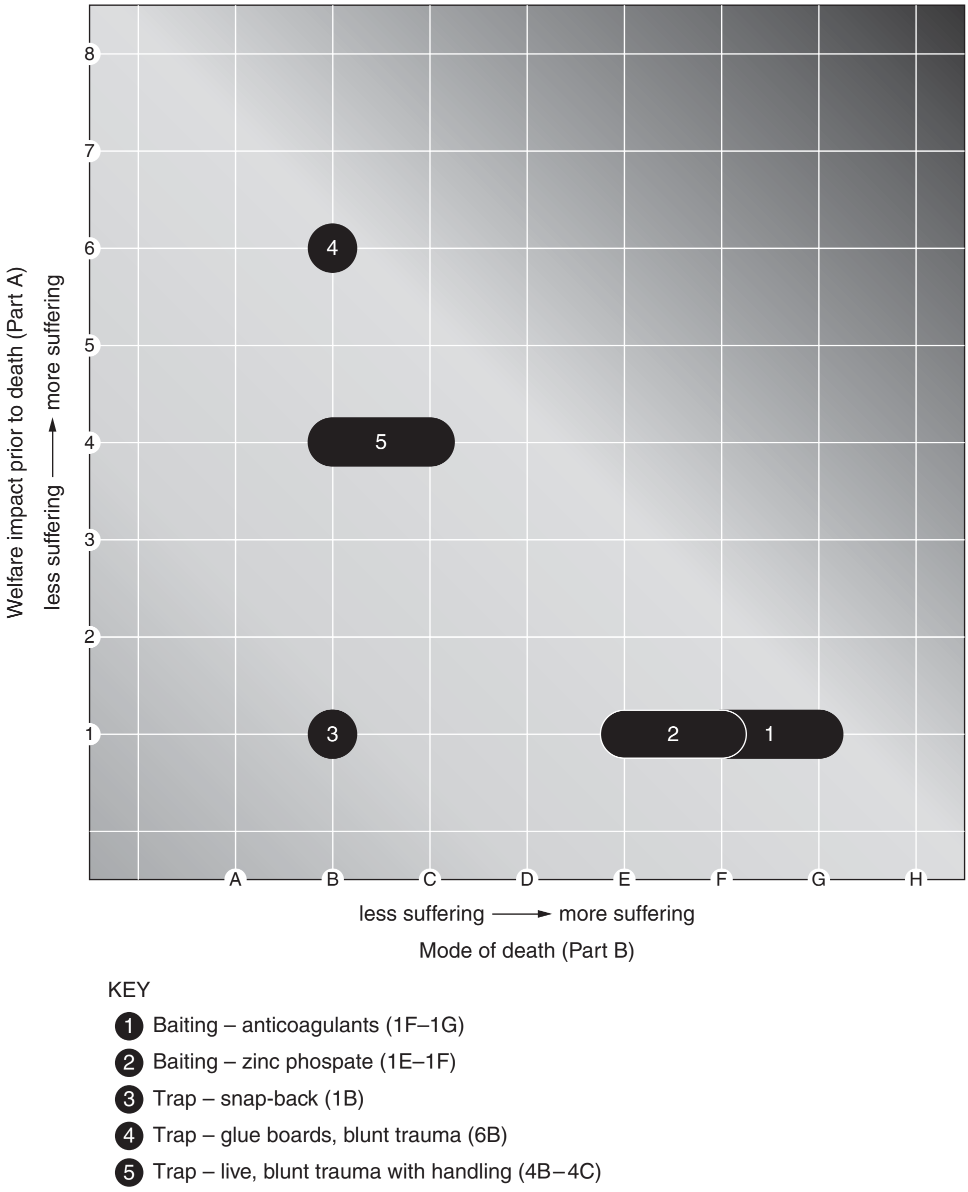

Fig. 15.5. Relative humaneness of rodent-control methods as assessed by the Australian Government and based on a model developed by Sharp and Saunders (2008).

average it took 6.5 min for animals to become unconscious (Talling and Inglis, 2009). However, no new proposals for Humane Trapping Standards have come forward from the EC since the release of this research. For traps used to catch or kill small rodents, such as mice and rats, no attempt has ever been made to establish European Standards, even though these are urgently needed to ensure that only humane traps are placed on the market.

Besides the Australian model of Sharp and Saunders (2008) and the AIHTS, other organizations, such as the Universities

Federation for Animal Welfare (UFAW), have produced guidelines that should lead to the humane control of rodents (UFAW, 2009). UFAW concluded that deterring and proofing – to prevent rodent pest infestation – is the best and the most humane approach, and that only properly designed and set traps should be used. They further recommend that if rodenticides are used, they should only be used as instructed on the label so as to ensure that a lethal dose is taken.

Refinement

Further to the evaluation of the level of humaneness of current methods, these methods themselves are capable of refinement. For example, there is a line of research in which analgesic drugs are added to pesticides in order to reduce animal suffering (Marks *et al.*, 2009). Dutch researchers are investigating whether submerged traps to control muskrats can be modified to improve their humaneness by the addition of break-back traps into the cage. Increasingly, restraining traps are equipped with electronic devices to notify trappers, using mobile phone messages, that an animal is caught in one of their traps. This may significantly reduce the amount of time that an animal has to spend in a trap and therefore the duration of its suffering. Furthermore, guiding devices that lead mice and rats head first into break-back traps significantly reduce their suffering by increasing the likelihood of a quick and clean kill. It is to be hoped that, as new technologies are developed, current methods of rodent control will be continuously adapted and refined to become more humane.

Integrated Pest Management and Humaneness

A detailed description of integrated pest management is given in Chapter 13. This strategy involves the following principles: (i) continuous monitoring to prevent unexpected rodent outbreaks; (ii) proper identification of the pest species and an understanding of its biology; (iii) prevention through good sanitation and exclusion of pests through proofing; and (iv) use of a complete treatment strategy, including evaluation of the service conducted, in order to reduce the use of substances that can damage the environment, such as rodenticides. This approach is already far more humane than the old-fashioned approach in which poison was used without removing the causes of the pest problem, such as easy access to food sources and the availability of nest sites and harbourage. However, it would be even better if these principles were combined with the models of Sharp and Saunders (2008) and Yeates (2010). Thus, if prevention and monitoring cannot remove pests completely, and lethal methods need to be used, the most humane methods, such as break-back traps, are employed first, before the less humane methods, such as anticoagulant rodenticides, are implemented.

Conclusions and Future Directions

It is evident that rodents respond to pain behaviourally and physiologically, that they exhibit complex cognitive abilities and that they show forms of empathy towards social conspecifics which are in pain. This level of consciousness in rodents warrants a careful approach when putting in place control measures against them that may cause them pain or stress, such as trapping and killing. Current methods used to control rodents differ in their humaneness. Proofing and hygiene measures are the most humane, because they do not involve killing rodents at all; these are followed by the use of break-back traps. Other methods, such as the use of glue boards and rodenticides, are much less humane. So far, in most European countries, legislation and policy guidelines do not make use of this knowledge on humaneness in rodent control, resulting in an approach which is mostly driven by cost efficiency. Clearly, an IPM approach, with an additional step to ensure that the methods used minimize harm, is likely to result in more humane pest control and, in the longer term, to be more cost efficient (see Chapters 3 and 5).

In order to increase the level of humaneness of rodent control it is necessary that governments, in consultation with stakeholders from among those who require services of rodent control, from among those who provide them, as well as from animal welfare interests, should:

1. Establish legitimate purposes for rodent control.
2. Develop and implement humane rodent-control standards, including the provision of best practice guidelines.
3. Test current control methods against these standards.
4. Approve for use only products and methods that comply with these standards.

Finally, the professional pest controller is the main interface with clients for rodent-control services. Therefore, next to strict legal regulation and a clear policy framework, an important step towards more humane pest control is for pest controllers to be aware of all the facts on legislation and on humaneness in rodent control and best practice, and to transfer this knowledge to their clients.

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16 Environmental Impacts of Rodenticides

R.H. Smith[1] and R.F. Shore[2]
[1]*School of Applied Sciences, University of Huddersfield, Huddersfield, UK;* [2]*NERC Centre for Ecology and Hydrology, Lancaster Environment Centre, Lancaster, UK*

Introduction

It is usually very difficult to control a pest (the 'target') using chemicals without causing some collateral damage to other ('non-target') species. Non-target damage should, of course, be minimized. Whether or not non-target damage is regarded as significant usually depends on whether only a few individuals are affected or whether there is an impact on the wider population. A few deaths of individuals may quickly be compensated for by density-dependent processes (see Chapters 1 and 5), for example by increased births, fewer deaths or compensatory migration. Effects on populations are, however, of concern, especially if those effects continue into the next generation. In the case of animals or plants of conservation interest, it may be that no accidental death or impairment is acceptable. In addition, it is often regarded as unacceptable to cause suffering to higher organisms such as birds and mammals. All of these concerns involve value judgements that differ between contexts and societies, and often within societies. Different interests and values must be balanced and weighed up in a benefits–harm analysis. The trade-off between benefit and harm that is acceptable is a function of the legislative framework, the pressure to reduce pest damage, and what is commercially and ethically acceptable within a particular market/society.

Much of the public concern about the potentially adverse effects of pesticides derives from the well-documented impacts of organochlorine insecticides on populations of predatory birds in Western Europe and North America (Newton, 1998). This example describes an historic mistake with several messages relevant to rodenticides. First, it describes a situation that arose some 50 years ago with the widespread application of novel agrochemicals in order to increase food production, but whose lethal effects on certain bird species were not understood (Newton, 1979). This mistake would be less likely to occur today because direct toxicity in birds would be detected at an early stage of research and development (see Walker, 1993), although compounds that vary markedly in the severity of the effects they cause in different species may still cause problems. The veterinary use of diclofenac in South-east Asia is one such example (Oaks *et al.*, 2004). Secondly, the consequences extended over many years after the problem of toxicity was first recognized because of the effects of persistent metabolites on reproduction in birds (Ratcliffe, 1967; Cooke, 1973; Newton, 1998). Severe sublethal effects of persistent chemicals would be less likely to occur today because the environmental fate of pesticides and their metabolites is a major concern to both the agrochemical industry and legislators, though the sublethal effects of long-term exposure may be difficult to detect (Smith, 1993; Walker, 1993). Thirdly, the effects of organochlorine insecticides on bird populations were documented in a way that would not be possible for other groups of organisms. Dead birds attracted attention and population-level effects were detected because birds are relatively conspicuous, most people consider them attractive, and there are better data on population trends for birds (e.g. O'Connor and Shrubb, 1986) than for other vertebrates. While there is no doubt that rodenticides kill a range of non-target species, it is the accidental killing of birds that attracts most attention.

In this chapter, we will first consider why we expect there to be problems with non-target effects as a result of rodent control, and then consider how better scientific understanding of the underlying ecology might enable us to assess, and perhaps to reduce, risk. We shall refer to the legislative approach in the European Union (EU), which is currently the Biocidal Products Directive or BPD (Directive 98/8/EC, recently superseded by Regulation (EU) No 528/2012). Our main focus is on understanding how biology, and in particular population biology (Smith, 1999), affects the environmental risks resulting from the use of rodenticides. In this respect, our chapter will be very different in emphasis from Brown (1994) in the first edition of this book, because we now have much more data available on the underlying biological processes. We shall summarize the conventional, tiered approach to environmental risk assessment (ERA) but those who would like more detail should refer to the chapter by Brown (1994) in the first edition, most of which is still relevant to understanding the approach to ERA that is taken in the EU.

We shall concentrate on anticoagulant rodenticides, as they are the most widely used chemicals in rodent control. Anticoagulants are of particular concern to regulatory authorities for several reasons:

- They are seen as candidate PBT compounds (PBT = persistent, bioaccumulative and toxic).
- In the EU, they may also be classified as CMR compounds (CMR = carcinogenic, mutagenic and reprotoxic).
- The simplest ERA statistics place them well outside acceptable risk levels at the first tier of assessment (see later).

Why Might Rodent Control Have Environmental Impacts?

Rodent control using chemicals can affect non-target species in a variety of ways. Most attention is given to the adverse effects on predators, especially predatory birds, which are exposed to *secondary poisoning* through eating poisoned prey. Predator populations generally take longer to recover than their prey because they have a lower reproductive rate as a consequence of longer time to maturity, longer intervals between reproductive attempts and producing fewer offspring at each reproductive attempt. Animals that compete with rats for food are more directly affected by *primary poisoning* through gaining access to bait. These are mammals and birds that are more comparable to the target rodent pests in terms of body size and life-history characteristics that contribute to reproductive rate (e.g. sparrows, *Passer domesticus*, wood mice, *Apodemus sylvaticus*, and voles).

Although rodent control is usually very targeted compared with, say, spraying with insecticides, there are specific factors that contribute to both hazard and exposure, and these are discussed below.

The physiology of rodents is very similar to that of non-target mammals and birds

Rodent control targets a particular order of mammals (the Rodentia), but all warm-blooded vertebrates (birds and mammals) have very similar physiologies. Indeed, other vertebrates, such as reptiles, amphibians and fish, are not so different either, especially when compared with invertebrate animals and plants. This is why mice and rats are the most commonly used laboratory animals in the development of medical and veterinary pharmaceutical products; mice and rats are used as surrogates in studies to help predict any adverse effects of medicines, pesticides and other chemicals precisely because their overall physiology and their biochemical processes are similar to those of humans and domesticated vertebrates. It is, therefore, difficult to develop chemical rodenticides that do not adversely affect other vertebrates that are exposed to them. Thus, many or most chemical rodenticides are hazardous to many other vertebrates, and whether or not they pose a risk depends on the level of exposure of the animal concerned. Environmental risk is a function of both chemical hazard and environmental exposure (see equation), and controlling exposure is usually the key to minimizing non-target effects.

$$\text{Risk} = f(\text{hazard, exposure})$$

The most effective and commonly used chemical rodenticides are the anticoagulants (see Chapter 6), which were developed from their original role in cardiovascular therapy because their delayed action prevents the development of conditioned taste aversion or 'bait shyness' (see Chapter 1; also O'Connor (1948) and Baker *et al*. (2007)). Birds, mammals and other vertebrates share the same blood clotting mechanism and so they are all more or less vulnerable to the toxic effects of anticoagulants. There can, however, be substantial variability in susceptibility between species, especially to some of the earlier, first-generation anticoagulants (see Table 6.2 in Chapter 6). Furthermore, most anticoagulants developed since the mid-1960s should be considered hazardous to *all* mammals and birds.

Delayed action of anticoagulants leads to overdosing of targets and exposure of predators

Ingestion of rodenticides would ideally be self-limiting such that the target pest took in only sufficient to cause death. The delayed action of anticoagulants, though, inevitably leads to overdosing. Harmful effects of anticoagulants only appear after the manufacture of clotting factors is blocked and the clotting factors circulating in the blood are used up, so rats and mice continue to feed for ≥2 days after ingesting a lethal dose. During this time, the intoxicated rodents continue moving around and feeding, effectively becoming parcels of poison on four legs, and leading to the exposure of their predators to the anticoagulant circulating in their bodies.

It is true that, when the toxic effects of anticoagulants take effect, rodents will reduce activity and feeding, so that body levels of anticoagulants will begin to decline, mostly through excretion. Rodent behaviour may also change in a way that may increase the exposure of their predators to anticoagulant. While the target rodents may in due course huddle in their nests and die underground, a study reported by Cox and Smith (1992) using time-lapse video recording of common rats, *Rattus norvegicus*, in an enclosure showed that intoxicated rats observed lost their normal tendency for a nocturnal pattern of activity (described in more detail later in the section *Adaptive behaviour and environmental impacts*).

Intoxicated rodents that die of internal bleeding without being taken by predators may then be eaten by scavengers, and the rodent carcasses will contain amounts of anticoagulant greater than was necessary to kill them. Brakes (2003) observed how captive red kites, *Milvus milvus*, selectively chose to eat the viscera of (non-poisoned) rat carcasses and also had a selective preference ranking for different parts of the viscera:

small intestines > liver > urinogenital organs

This sort of selective feeding behaviour may, unfortunately, also act to increase exposure to anticoagulants if it occurs in the wild. This is because the guts of poisoned rodents may contain undigested or partially digested rodenticide bait and, once absorbed across the gut, much of the anticoagulant rodenticide is bound to liver tissue. Thus, the main feature of anticoagulants that makes them so effective (delayed action) unfortunately leads to increased exposure of non-target predators and scavengers by overdosing rats beyond lethal doses.

Contract pest-control practice may have led to higher than necessary exposure of non-targets

Controlling rodents with chemical rodenticides according to best practice is expensive and requires a level of expertise. Many farms develop rodent problems in the first instance because the farmers cannot find the time to carry out basic hygiene and proofing measures (Chapter 5). It is equally difficult for them to find the time needed to carry out rodent control, and they commonly use professional pest-control operators (PCOs) to do this for them.

The business model followed by most PCOs was developed decades ago by the major players in the service-contract industry and has not changed much, even though the chemical rodenticides that they use are both more persistent and more toxic than when the business model was developed. In essence, PCOs usually establish service contracts that include a certain number of routine visits at regular intervals, with additional visits if necessary, for which there will be an extra charge. The business model was developed when first-generation anticoagulants requiring surplus baiting regimes (see Chapter 6) were the only effective option. Competition between pest-control companies has always been intense, with small profit margins for each contract, and profit could only be increased by increasing the number of contracts serviced by the pest-control technicians. All of this led to bait being made available permanently at bait points that were inspected rather infrequently (perhaps only once a month), inevitably increasing the exposure of non-target small mammals and birds to toxic bait.

Recognition of the increased potential for harm associated with second-generation anticoagulants has led to changes in instructions on rodenticide labels, which every user is obliged to follow. Bait points must be inspected regularly and bait removed at the end of a treatment. There are, however, economic pressures to do only as much as is required rather than what is ideal. For example, the pressure on pest-control technicians to cover as many sites as possible makes it unlikely that they will spend a lot of time searching for poisoned rat carcasses, notwithstanding label instructions to remove carcasses. Likewise, surveys of rodenticide use by farmers on agricultural holdings also indicate that searches for poisoned carcasses are rarely carried out (Tosh *et al.*, 2011).

A beneficial development since the first edition of this book is the acknowledgement by the rodenticide industry and PCOs that there may be a risk to non-target wildlife from rodenticides. This has been the result of extensive research and monitoring studies that have shown that there is extensive exposure in a wide range of non-target species (Chapter 17). A key consequence has been the establishment of 'best practice' guidelines. An example of an organization and a voluntary accreditation process that aims to reduce environmental impacts is the UK Campaign for Responsible Rodenticide Use (CRRU: http://www.thinkwildlife.org/crru-code/), and many PCOs are signed up to the CRRU Code of Practice (see later).

Audit schemes lead to prophylactic use of rodenticides

A further factor here is the introduction of audit or 'passport' schemes run by, for example, AIB International, the British Retail Consortium and major supermarket chains. There is great pressure on farmers and other suppliers to produce food that is not only nutritious and safe but also free from any detectable contaminants, such as rat hairs, other tissues or faecal material. The finding of unwanted contaminants in produce tends to generate bad publicity and audit schemes help to protect business as well as the health of the consumer. The main aim of these schemes, which cover the food supply and distribution industries, is to protect the safety/quality of the human food chain (see Chapter 11). The standards set by these schemes are comparable across the world and help to achieve the protection of human food supplies. There is, however, an unintended negative consequence for non-target wildlife. Farmers risk having their produce rejected if they fall foul of audit schemes, and audit schemes inevitably encourage routine perimeter baiting and other prophylactic measures that verge on permanent baiting 'just in case'.

Game bird rearing and rat control take poison well away from buildings

Farmers in many countries have diversified to find new sources of income. In countries such as the UK, rearing game birds such as pheasants for recreational hunting has become an important source of income for large farms and estates. Full-time gamekeepers are employed to ensure a good supply of birds for the shooting season. The birds are encouraged to remain on the estate by supplying large quantities of grain in hoppers, known as 'pheasant feeders', and these attract rats and other small mammals. In addition, strips of 'cover crops', such as maize, are grown to provide shelter for the birds. These provide both shelter and food for rats, and can lead to the build-up of large numbers of rats that are detrimental to the game-bird enterprise. Gamekeepers are typically skilled at trapping or shooting vermin, but they use substantial amounts of rodenticide bait in the farm environment well away from buildings (McDonald and Harris, 2000), presumably because of the scale of their rat problems in places where they are feeding game birds.

How Environmental Risk is Assessed and Managed by the Registration Process

New pesticides and biocides are registered for use in agriculture only if they satisfy safety criteria for those applying them, the consumers eating the crops and the environment into which they are released. Environmental risk assessment or ERA (Brown, 1994; Brown *et al.*, 1988) is used to predict the environmental fate and potential effects of pesticides/biocides on non-target species by a stepwise or tiered process. In the EU, a tiered or stepwise approach has been designed to make efficient use of resources, because a chemical passes on to the next (more expensive) tier only if it fails the safety criteria at a lower level. The requirements of the US Environmental Protection Agency (EPA) are similar to those of the EU regulatory authorities, and are also based on a stepwise approach. There are four tiers to this regulatory stepwise approach. The higher numbered tiers are the most realistic (i.e. the closest to field conditions). The lower tiers are the most conservative in terms of assessing risk.

Tier 1

The first tier is an initial review of data based on physico-chemical properties of the chemical and its toxicological profile, allowing an assessment of hazard (toxicity) and a preliminary assessment of risk (likelihood of exposure to the hazard). Some pesticides may have such low toxicity (T) to vertebrates that it is clear that no risk will result from their use (Urban and Cook, 1986), and no further investigation is necessary, but this will not be the case with rodenticides or many other broad-spectrum biocides. The likely fate of the compound in the environment is then examined to predict the maximum expected environmental concentration and consequent potential environmental exposure (E). A first-tier prediction of risk is then made by comparing toxicity to exposure in some form. In broad terms, a compound is judged acceptable at the first tier if $E < T$, i.e. if the levels of exposure are sufficiently low not to cause harm.

In practice, the measures used in Tier 1 assessment are the predicted environmental concentration (PEC) and the predicted no-effect concentration (PNEC), combined as the PEC/PNEC ratio, which should not exceed one for acceptability. Uncertainty factors are also typically applied to either the PEC and/or PNEC to make the assessment conservative; their use is intended to account for uncertainties in the assessment, such as whether compounds are equally toxic to all species. Not surprisingly, PEC/PNEC ratios for modern anticoagulants are massively greater than one (actually of the order of 10^3–10^5 or higher) for characterizing the risk of both primary and secondary poisoning for mammals and birds at Tier 1 (Luttik *et al.*, 1999).

Tier 2

The second tier uses supplementary studies to examine routes of exposure of non-target species (Hardy, 1990) and toxicological effects. These refinements aim to incorporate factors such as, for example, estimated food consumption, in order to refine estimates of exposure. The resulting PEC/PNEC ratios are still unacceptable by very wide margins for modern anticoagulants (Luttik *et al.*, 1999).

Tier 3

The third tier is nearer to realistic patterns of use in the field and is based on an examination of 'worst case' scenarios in semi-field (e.g. large enclosure) or field trials. Simulated field trials look at primary and secondary exposure. An open-field trial, with intensive studies of residues in the field, effects on non-target animals and quantitative assessments of risk, is used to judge whether the effects of the test compound(s) are acceptable or not.

Tier 4

The final tier is post-registration monitoring, which provides a means of identifying problems that might not have been picked up at earlier stages. In the UK, the responsible government department, Department for the Environment, Food and Rural Affairs (Defra), operates a pesticides incidents scheme whereby any wildlife deaths reported that may be attributable to pesticides are investigated under the Wildlife Incident Investigation Scheme, known by the acronym WIIS. Because the WIIS focuses on mortality incidents where there is a suspicion that pesticides are involved, it does not provide unbiased information on how widespread exposure may be, but it does give an overview of whether pesticides may or may not be causing mortalities. In addition, in the UK, there is also a non-statutory monitoring scheme, the Predatory Bird Monitoring Scheme (PBMS: http://pbms.ceh.ac.uk/), which does quantify the extent of exposure to rodenticides in wildlife by monitoring residues in three sentinel predatory bird species. More details of this and other residue-monitoring schemes are given in Chapter 17.

Under the Biocidal Products Directive in the EU, rodenticides are evaluated and approved for use ('listed') across the EU. Nevertheless, individual member states can also impose local restrictions or conditions of use based on perceptions of national requirements. Over most of the EU, most second-generation anticoagulant rodenticides (SGARs) are registered for use in and around buildings, which would preclude open-field use or use around pheasant feeders away from buildings. In contrast, the UK has, until recently, used the more restrictive classification 'indoors only' for brodifacoum, difethialone and flocoumafen, while bromadiolone and difenacoum may be used 'indoors and outdoors', with no specific restriction that they should only be used around (i.e. close to) farm buildings, as in the rest of the EU. The indoors/outdoors classification used in the UK is intended to protect non-target wildlife. An unintended consequence is that use of bromadiolone and difenacoum in large quantities away from buildings on game estates has been allowed in the UK, and may have been a major source of wildlife contamination by SGARs (Buckle *et al.*, 2011).

The stepwise approach to ERA seems to be reasonable and generally to work well, although it only takes partial account of the complex ecology of free-living vertebrates. It is based almost entirely on effects observed in individuals, and only in Tier 3 is there an attempt to look at effects in populations. Even there, the approach is based on a rather static view of populations with little appreciation of spatial effects and population structure.

Population Biology and Environmental Effects of Rodenticides

Smith and Sibly (1985) describe population biology as a triad comprising population dynamics, adaptive behaviour and evolutionary genetics. This view of population biology recognizes that changes in numbers (population dynamics) affect and are affected both by adaptive, behavioural responses of individuals and by longer term, evolutionary changes in a population. It is well known that exposure to sublethal levels of pesticides may affect behaviour (e.g. Cox and Smith, 1990) and may also lead to the evolution of inherited resistance. Changes in both behaviour and rodenticide resistance are relevant to rodenticide ERA.

Individuals and populations

A population can be broadly defined as those animals or other organisms that are present in one place at one time. This definition is not always straightforward to apply because 'place' may be difficult to define precisely, especially for animals such as birds that are relatively settled for parts of the year but may move or migrate over large distances at other times.

The four processes that affect population size are birth, deaths, immigration and emigration (see Fig. 5.1a in Chapter 5). When we think about the environmental effects of pesticides or biocides, we usually think in terms of effects on the death rate. However, experience of how organochlorine pesticides affected wildlife populations in the past tells us that birth rate may also be affected by sublethal levels of toxicants. Immigration and emigration rates might be affected directly if the migration behaviour of animals is changed by exposure to pesticides, but more important than this is the way that migration rates, and indeed birth and death rates, respond to changes in local population density in real populations (Newton, 1998). Both the birth rate and the death rate might change with population density in natural populations. In general terms, birth rate declines, whereas death rate increases, with increasing population size; this is known as density dependence and may lead to the regulation of a population around some average level, known as the carrying capacity. If exposure to pesticides simply leads to an increase in death rate for a short period of time, we generally expect compensation in the population growth rate, which will tend to restore population numbers to the original level. This means that the population-level effect of pesticide exposure will be short lived unless either exposure is repeated, or persistent residues continue to have an effect, or the relationship between death rate and population size is fundamentally altered and thereby alters the carrying capacity.

Spatially structured populations

Most populations of animals are not distributed uniformly across the landscape. In many cases, patches of suitable habitat are separated from other such patches by unsuitable habitat, and movement between patches is restricted. This introduces the concept of the '*metapopulation*', a modern view of population dynamics that is relevant to both target and non-target species (Smith, 1995).

In the classical metapopulation structure, local populations are concentrated in patches of resource and there is limited movement between local populations, mostly between adjacent patches (see Fig. 5.1b in Chapter 5). This is often described as a metapopulation structure, and the dynamics of the metapopulation depend on both the dynamics within local populations and the movement between those local populations. The rate of movement between local populations may be density dependent in a similar way to birth and death rates, and a large effect on a local population might be compensated for more or less rapidly by migration from a nearby local population. The impact of a rodenticide on the dynamics of the metapopulation would then depend on the extent to which one or more patches are affected, and also the synchronization of those effects (patches might correspond in broad terms to fields or forests or farms). Asynchronous treatment of patches would be expected to have less effect on the overall dynamics of the metapopulation than synchronized treatment of all the local populations, as a consequence of density dependence and movement between patches.

This last point is relevant both to increasing the effectiveness of rodent control and to reducing impacts on non-target species. Synchronized control of rodent pests over a large area is almost always going to be more effective than the same amount of control effort used asynchronously (at different times in different places). Unfortunately, synchronized rodent control will also have a more widespread, deleterious effect on some non-target species, both through the direct effects of rodenticide and through indirect effects on predators of having their prey removed over a large area all at once.

Many species of particular conservation interest are, unfortunately, relatively slow breeders, and recovery time may, therefore, be relatively long, certainly compared with the pests against which pesticides are targeted. An interesting example of the recovery of a bird species in the context of a spatially structured population is provided by Newton in his study of the sparrowhawk, *Accipiter nisus*. The woodlands of Northamptonshire, in the UK, have gradually been recolonized by the sparrowhawk since the use of organochlorine pesticides ceased, and Wyllie and Newton (1991) provide an example of the way that density-dependent migration has contributed to the metapopulation dynamics of the process. In this case, though, not all patches are equal: some woodlands do not provide sufficiently good habitat for births to match deaths and support only ‘sink’ populations. A sink population (where deaths exceed births) can only be maintained by migration from more productive woodlands (where births exceed deaths), known as ‘source’ populations. The population dynamics of this sort of structure are known as source–sink dynamics.

One problem with a source–sink structure is that, on a landscape scale, it can appear that a population is thriving because many or all patches are colonized. Wiping out a source population, however, would eventually lead to extinction of the sink populations that are maintained by migration from the source. Thus, a population with a source–sink structure is not resilient to perturbations that affect the source populations and can go into general decline if the few source populations are wiped out or have their productivity reduced, perhaps as a result of exposure to rodenticides.

Adaptive behaviour and environmental impacts

Most of the behaviour of wild animals can be described as adaptive in the sense that it has evolved because it increases the fitness of individuals showing that behaviour (Smith and Sibly, 1985). Pest rodents show a variety of behaviours that reduce their chances of being predated, for example nocturnal activity, thigmotactic behaviour and neophobia (Chapter 1). Predators have a range of behaviours that help to maximize their rate of prey intake and hence their survival and reproduction.

The behaviour of both prey and predator can be modified by exposure to pesticides or biocides (Hart, 1990), although rather little is known about the effect of sublethal doses of these on the behaviour of predators. In general, prey species exposed to poisoning show lethargy, apparent lack of awareness of surroundings and unwillingness to fly or to (otherwise) move more than necessary. Cox and Smith (1992) have described such changes in rat behaviour in the days between the consumption of anticoagulant poison and death. Following exposure to anticoagulant rodenticides, rats seemed to lose their thigmotactic response and to use the edges of their environment less and open areas more; indeed, within 3 days of consuming a lethal dose of anticoagulant, rats were observed standing still in the open for up to 20 min at a time, and the time spent in the open as opposed to around the edges of the environment changed from 16 to 79% within 4 days. Diel activity rhythms also changed such that, within 48 h of intoxication, rats were active for a greater percentage of time in the light and less in the dark, which is the reverse of normal behaviour.

Changes in the behaviour of prey can substantially affect the risk of exposure of predators to secondary poisoning from consuming intoxicated prey. This change in behaviour could have effects on potential predators, in that rats moving in the open are more easily seen and their reduced motion would make them easier to catch. It is known that nocturnal hunters such as owls are more successful at hunting when their prey is foraging in the open rather than under cover (Southern and Lowe, 1968; Kotler *et al*., 1988). Behaviour that makes prey stand out as 'unusual', such as the staggering shown by the rats described by Cox and Smith (1992), has also been shown to lead to selective predation (Rudebeck, 1951; Mech, 1970). The effect of the rodenticide on rats in changing their normal, adaptive behaviour would seem to make them more vulnerable to predators. The profile of predators might also alter; change in diel activity could expose rats to diurnal hunters such as weasels (Sleeman, 1989), kestrels, buzzards and foxes, while nocturnal predators such as owls might become less exposed.

Rodenticide resistance increases exposure of predators and scavengers

Resistance to anticoagulant rodenticides appeared in the UK within 7–8 years of the introduction of warfarin, and has been reviewed by Smith and Greaves (1987) and Greaves (1994), and in Chapter 9. The main practical problem of resistance is that rats become difficult to control (Cowan *et al*., 1995), but there could also be effects of resistance on the environmental impacts of rodenticides.

The problem arises as follows. In areas with high levels of resistance to the rodenticides available for outdoor use (documented over much of the southern half of the UK: see Chapter 14 and Fig. 3 in Buckle and Prescott, 2012), large quantities of bait can be used as part of outdoor treatments that are either wholly or partially ineffective. Resistant rats can feed on the bait with few or no ill effects. Each resistant rat potentially provides a substantial parcel of poison to any predators that might attack it.

How large an effect is this? In a replicated field study comparing body loads of the anticoagulant coumatetralyl in rats between areas with resistance (Berkshire, UK) and areas with no resistance (Leicestershire, UK), a non-metabolizable, chemical bait marker was used to quantify bait consumption by individual rats (MacVicker, 1998; Smith, 1999). In addition, whole carcass body residues of coumatetralyl were measured. It was found that rats from populations with resistance consumed on average around five times more bait and that their body loads of anticoagulant were about five times higher than those of rats from populations without resistance. Most of the rats from the populations with resistance survived these very high doses and had to be trapped in order for the analyses to be carried out. In contrast, Atterby *et al*. (2005) found a smaller difference in body loads (less than two times) between resistant and susceptible rats, but their laboratory study looked at equilibrium body loads rather than at the higher, transient body loads in rats encountered by predators in field conditions. Hence, resistance in rats may substantially increase the exposure of their predators to anticoagulants at any time during the treatment of an infestation. Add to this the fact that resistance increases treatment time, perhaps indefinitely, and we see that anticoagulant resistance is likely to increase substantially the risk of accidental poisoning of those predators that feed on rats and inhabit areas where resistance is prevalent.

Environmental impacts mediated by competitors of rats

It is easy to forget that there are several species of small mammals and birds that eat the same sorts of food as rats and mice. If they can access poisoned bait, these competitors may be killed, or they may act as vehicles that carry poison to predators that might not feed on rats. In practice, it is all but impossible to design a bait box that a rat can access but a smaller rodent cannot. Thus, non-target rodents that are common in the agricultural environment, such as the wood mouse, bank vole, *Myodes glareolus*, or field vole, *Microtus agrestis*, may all feed at bait boxes placed around farm buildings.

Brakes and Smith (2005) carried out exposure studies of non-target small mammals alongside routine rat control at five UK sites. The three non-target species mentioned above all fed on poisoned bait, and 49% of individuals in local populations were known, by use of markers, to eat the bait. Local populations declined by 56% on average, compared with reference populations (no rat control), which increased by 9% over the same period. After a 3 month follow-up period without rat control, small mammal populations had still declined by 51% compared with a 5% decline in reference populations. This demonstration of substantial consumption of bait by non-target small mammals may help to explain why predators such as the kestrel, *Falco tinnunculus*, that do not commonly feed on rats show such high levels of exposure to anticoagulants (see Chapter 17).

Modelling environmental exposure

Cox and Smith (1990) and Smith *et al*. (1990) proposed a compartment model of rodenticide ecotoxicology in order to combine the main components of the rodenticide system. Smith *et al*. (1990) presented some quantitative predictions based on a simulation model that did not include population dynamics or genetic changes, but did model physiology and behaviour based on laboratory and field data. Their generic model of rodenticide ecotoxicology is shown in Fig. 16.1.

Smith *et al*. (1990) modelled two compounds with contrasting LD_{50} values (25 mg kg^{-1}, typical of first-generation anticoagulants, and 0.25 mg kg^{-1}, typical of SGARs). For the more toxic compound, most rats died with residues higher than would be expected if they had ingested and fully retained an LD_{50} dose, because the delayed action of anticoagulants meant that they continued to feed for a period of time after the ingestion of a lethal dose. The simulation results for the

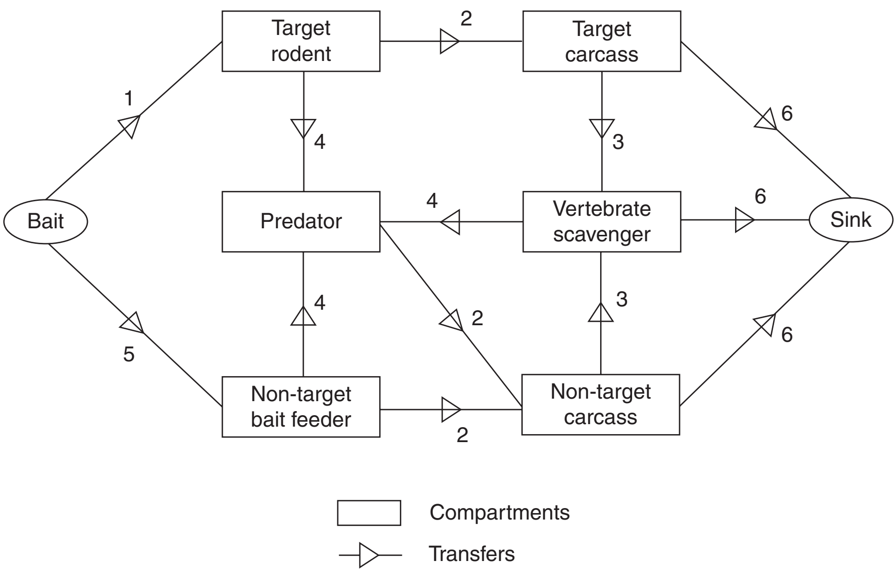

Fig. 16.1. Conceptual model of rodenticide ecotoxicology. There are six transfer processes that need to be quantified to make the model predictive: (1) primary feeding on poison bait by the target rodents; (2) mortality due to primary and secondary poisoning of target and non-target organisms; (3) feeding on carcasses by vertebrate scavengers; (4) predation of target and non-target vertebrates; (5) primary feeding on poison bait by non-target vertebrates; (6) transfer of poison to soil from carcasses. (After Smith, Cox and Rampaud, 1990.)

more toxic compound gave residue values very close to the mean carcass residue level of 3.2 mg kg^{-1} reported by Dubock (1984) for saturation baiting with an anticoagulant (brodifacoum) that has a similar LD_{50}. Residue levels were substantially higher for the less toxic compound, but represented lower risk because they were not 100-fold higher, which was the difference in toxicity (LD_{50} value) between the two compounds. In addition, with the less toxic compound, most carcass residues were lower than would be expected if an LD_{50} dose had been ingested and retained. This was because of the rapid daily elimination (assumed to be 30%), which also outweighed any accumulation through continued feeding.

When modelled residues were expressed as rat acute oral LD_{50} equivalents, the more toxic compound was seen to represent a greater potential risk to scavengers because of their exposure to residue levels in carcasses (Smith, 1999). The results suggested, however, that the less toxic compound might represent a greater risk to *predators* because rats would be wandering around carrying substantial levels of the compound for much longer, and exposure would, therefore, be increased. The model was found to be fairly insensitive to uncertainties in exact values of parameters even though its representation of elimination and accumulation was quite crude. In particular, the model assumed a simple, one-phase elimination model (summarized by a single-figure half-life parameter), whereas we know that anticoagulants are eliminated in a biphasic process, with the rapid, initial elimination of circulating compound, followed by slower elimination from binding sites (Huckle *et al.*, 1988).

Further exploration of the model suggested that the concentration of active ingredient in bait for the more toxic compounds might safely be reduced without a substantial reduction in efficacy and, in consequence, the residue levels in the carcasses would also be reduced. This sort of mechanistic effect model based on certain features of the population biology of rats could prove to be a useful aid in optimizing the concentration of active ingredient for compounds with different levels of toxicity and in helping to reduce the exposure of non-target animals to rodenticides.

Risk Mitigation

Alternative chemicals to anticoagulants

There are currently no compounds on the market that are as effective in rodent control as anticoagulants, but it is worth considering whether there are alternatives that might be good enough, yet avoid the known adverse effects of anticoagulants.

Calciferols were hailed as candidate alternatives in the 1970s because they also have a delayed action, although they are less stable than anticoagulants in damp conditions and so have been used mainly in dry situations (especially against mice). There is, though, experimental evidence that the symptoms of calciferol poisoning (hypercalcaemia) are not sufficiently delayed to overcome bait shyness completely in rats (Prescott *et al.*, 1992). Calciferols have the major benefit that there is no evidence of inherited resistance to them and they could, therefore, be used as a second line of attack when anticoagulant resistance is present. Eason *et al.* (2000) investigated the risks to companion animals of non-target and secondary poisoning from using cholecalciferol and concluded that there is a risk of secondary poisoning, but that it is lower than with anticoagulants. The registration of calciferols has, however, lapsed in the EU where companies have chosen not to provide the supporting information required by the registration authorities for inclusion in Annex 1 of the BPD.

Alphachloralose is a narcotic used for mouse control and has the potential to cause adverse effects in non-target organisms. In the EU, environmental exposure to this rodenticide is limited because alphachloralose is only registered for indoor use against rodents.

Bait placement and composition

The way that rodenticide bait is applied is a key element in minimizing the risk of accidental poisoning on non-target organisms. In the UK, the CRRU has promoted best practice through its Think Wildlife campaign. The CRRU web site should be consulted for more detail, but the elements of the CRRU code of practice are as follows:

- Always have a planned approach.
- Always record quantity of bait and where it is placed.
- Always use enough baiting points.
- Always collect and dispose of rodent bodies.
- Never leave bait exposed to non-target animals and birds.
- Never fail to inspect bait regularly.
- Never leave bait down at the end of a treatment.

The composition of bait includes both the active ingredient and the medium that is used to make the bait attractive to the target pest species. Ideally, the bait should be more attractive to the target than to non-target species. In practice, other mammals, as well as birds, are likely to eat bait, whether it is presented as grain, formulated pellets or wax blocks, if it is accessible, and local populations of non-target mammals may be affected even if good practice is observed (Brakes and Smith, 2005).

Alternative and supplementary control measures

Alternative and supplementary measures can mitigate adverse effects if they reduce the exposure of non-target animals to chemical rodenticides; such measures do not need to replace anticoagulants entirely in order to achieve this. Some non-chemical alternatives are discussed in Chapter 5.

In general, habitats that are structurally complex are attractive to rats and other field rodents because they provide nest sites and reduce visibility and exposure to predators. Lambert *et al*. (2008) describe a replicated study that used radio tracking and population estimation before and after habitat management around farm buildings to study the impact of reducing habitat complexity on the ranging behaviour and survival of rats. Removing harbourage up to field margins reduced rat survival and activity around the farm buildings and appeared to be cost effective, although it was seen as a supplement to (rather than a replacement for) chemical control that ought to reduce the quantity of anticoagulant used on a farm, i.e. part of the integrated approach promoted by Singleton *et al*. (1999).

In a further development, Defra supported field studies in Yorkshire and Leicestershire, UK, aimed at reducing the use of anticoagulant rodenticides through ecologically based rodent management (Brown, 2007). The impetus for this work was concern about both humaneness (Mason and Littin, 2003) and the non-target effects of anticoagulants. There were two elements to the study, which was based on the concept of managing the rat population across the landscape:

1. Coordinating rat control over a large area (400 ha) rather than poisoning rats around farmyards in an uncoordinated way.
2. Incorporating systematic trapping into the control strategy to reduce the numbers of rats moving into farm buildings during the autumn.

One of the aims was to reduce the overall rat population in each of the 400 ha coordinated blocks compared with the uncoordinated reference areas, and this was achieved over a 2–3 year period. Along with this reduction, there was a concomitant reduction in the amount of anticoagulant applied. To date, only part of the study has been published, in conference proceedings (Etherington *et al*., 2009), though most of the results can be found in a PhD thesis (Brown, 2007). It does seem that the adoption of an integrated pest management (IPM) approach could significantly reduce the amount of rodenticide put out into the environment at the same time as controlling pest damage effectively.

Discussion

Whatever the process used in pesticide registration in order to avoid adverse environmental effects, it will always be necessary to monitor wild populations for unforeseen effects associated with pesticide use. In the UK, we are particularly lucky to have a large band of enthusiastic volunteers who monitor bird populations. Population monitoring of the sort coordinated by the British Trust for Ornithology (BTO) provides estimates of average population size of common bird species in different years in the UK.

Population monitoring alone, however, generates many more questions than answers. For example, there has been a decline in barn owl, *Tyto alba*, populations since the 1950s in the UK and other countries (Shawyer, 1987). It is known (and it is not surprising) that the residues of several anticoagulant rodenticides are found in barn owls in the UK (Chapter 17); but there is no evidence of significant adverse effects on barn owl populations of harmful levels of rodenticides in their mammalian prey. In fact, barn owl decline appeared to precede the introduction of SGARs into Britain. The exposure of barn owls, and other non-target species, to rodenticides may cause some concern, but the observed decline in barn owl numbers is more likely to be an indirect consequence of the earlier use of organochlorine pesticides and of subsequent changes in the agricultural management of grassland.

The argument for well-controlled replicated field experiments as an invaluable aid to understanding environmental effects has been made many times and in many places (e.g. Brown, 1990, 1994; Cox and Smith, 1990; Hart, 1990). The ecotoxicology model summarized in Fig. 16.1 can guide the design of field experiments and could be generalized to other pesticides, but it is possible that the system may become much more complicated when herbicides or insecticides are considered. The main value of this sort of quantitative approach to prediction is that it focuses attention on missing information and can help to direct effort towards collecting the important missing data. In addition, the modelling approach can allow the inclusion of what are now very basic and widely accepted ecological principles in order to move ecotoxicology away from effects on individuals and towards genuine prediction of the ecological effects of toxins.

The results for modelling rodenticide ecotoxicology that are presented here demonstrate the practical value of this approach, although it has to be admitted that this model is clearly only a first step that does not even include density-dependent effects in rat populations (e.g. Smith and Greaves, 1987). Future advances will link the ecotoxicology modelling approach to the sorts of models now routinely used in formulating pest-management strategies, and will include the incorporation of spatial as well as temporal features.

In this chapter, we have attempted to broaden the approach taken in the first edition of this book (Brown, 1994), by moving beyond a focus on regulatory requirements to try to establish a conceptual framework based around biology and, more specifically, population ecology. The aim is to develop an ERA for rodenticides that is more realistic than, for example, Tier 1 use of PEC/PNEC ratios, which have little relevance. This is still a work in progress. For example, we need to be able to predict more accurately the true level of mortality in non-target species of interest that is attributable in whole or in part to rodenticides. We need better linkage of environmental risk assessment to population dynamics (including spatial dynamics) in the field, and we expect that this will involve developing population models that are both realistic and predictive. We would hope eventually to see this better understanding guiding technological advances in delivery systems that would lead to reducing exposure to rodenticides to target species only. In the meantime, we support initiatives such as CRRU's Think Wildlife campaign that (in the words of Brown, 1994) help 'to ensure that successful rodent control is accompanied by safety to wildlife and the environment'.

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17 Monitoring Rodenticide Residues in Wildlife

R.F. Shore, M.G. Pereira, E.D. Potter and L.A. Walker
NERC Centre for Ecology & Hydrology, Lancaster Environment Centre, Lancaster, UK

Introduction

Rodenticide residues have been measured in wildlife to gain information on the scale of exposure and to assess the likelihood of associated adverse effects. Wildlife in this context refers to non-target species (i.e. species not targeted for control using rodenticides) other than domesticated and companion animals. Such monitoring has been needed because rodenticides are not target specific in their toxicity; wild vertebrates have the potential to be exposed to these compounds and to be potentially adversely affected by them. Exposure can be primary (rodenticide consumed directly), secondary (organism exposed by eating contaminated prey or other material) or a combination of the two.

Although there is a range of rodenticides with differing modes of action, the monitoring of residues in wildlife has largely involved the anticoagulant rodenticides (ARs). In particular, the second-generation anticoagulant rodenticides (SGARs), sometimes called ‘superwarfarins’, have been the focus. This is because of their widespread use, their enhanced acute toxicity compared with the older first-generation compounds, and their persistence in body tissues (WHO, 1995; Eason *et al.*, 2002; Vandenbroucke *et al.*, 2008). Compounds that are highly toxic can pose a significant risk to the survival of exposed individuals, while the combination of high toxicity and persistence enhances the potential for secondary poisoning in predatory, scavenging and omnivorous species.

Recent reviews of several SGARs under the European Union’s Biocidal Products Directive, or BPD (Directive 98/8/EC, recently superseded by Regulation (EU) No 528/2012), e.g. Elsmore (2010), have highlighted significant or unacceptable risk of primary and/or secondary poisoning of birds and non-target mammals from some SGARs. Nevertheless, their use has been authorized because of their overriding importance for human hygiene and public health; brodifacoum is an example (see ECHA, 2013). The concern in many countries is that widespread and/or intensive use of ARs, and in particular of SGARs, may result in mortalities among species that may be protected, rare and/or reintroduced, and that the incidence of mortality may be sufficiently high as to have an impact on their populations (Birks, 1998; Carter and Burn, 2000; Burn *et al.*, 2002; Ntampakis and Carter, 2005; Giraudoux *et al.*, 2006; Sage *et al.*, 2008; Olea *et al.*, 2009; Ross *et al.*, 2010; Coeurdassier *et al.*, 2012). To date, though, no population-level effects have been reliably recorded. Indeed, at least in the UK, populations of the species that are most frequently found to be contaminated with SGARs appear to be increasing (Buckle, 2013a).

The monitoring of residues in wildlife has typically taken two general strategies. The first, exposure monitoring, involves one-off or longer term monitoring studies that measure residues in wildlife species that have been found dead from various causes, were killed deliberately by illegal poisoning and by non-poisoning means (such as shooting) or were found sick/injured and submitted to rehabilitation centres (Fournier-Chambrillon *et al.*, 2004; Lambert *et al.*, 2007; Walker *et al.*, 2008a,b; Albert *et al.*, 2010; Dowding *et al.*, 2010; Elmeros *et al.*, 2011; Murray, 2011; Tosh *et al.*, 2011a). Data from such studies are used to indicate the general level of exposure of a population to rodenticides, although it can be argued that there are likely to be some inherent biases in sample collection.

The second, more selective, monitoring strategy involves measuring residues in wildlife suspected of having been poisoned; examples include the Wildlife Incident Investigation Scheme (WIIS) in Britain (Maltby, 2008; Health and Safety Directorate, 2013), the Wildlife Disease Surveillance System (SAGIR network) in France (Berny and Gaillet, 2008), and the programme of toxicology investigations conducted by the Instituto de Investigación en Recursos Cinegéticosa in Spain (Sánchez-Barbudo *et al.*, 2012). Mortality investigation studies are, by design, selective in their analysis of samples and so do not provide unbiased data on population exposure. However, they are invaluable in that they can demonstrate whether mortalities occur as a result of exposure to biocides or pesticides, including ARs, and, when monitoring is consistent, they provide information on whether the detection of such mortalities is changing over time.

The liver is typically the organ that is monitored for AR residues because it contains high-affinity binding sites and residues tend to be higher than in other tissues (Huckle *et al.*, 1988, 1989b). Analysis of other organs and stomach contents may also be undertaken when the aim is to determine whether the cause of a mortality incident is poisoning. The half-life for compounds in the liver varies between rodenticides (Huckle *et al.*, 1989a,b; Thijssen, 1995; Fisher *et al.*, 2003; Vandenbroucke *et al.*, 2008), but detection of residues in the liver indicates that there has been at least one exposure event before the death of the animal. In the case of the more persistent ARs, liver residues provide a signal of exposure that is integrated over weeks and months.

There have been some studies of AR residues in non-destructive samples, such as red fox (*Vulpes vulpes*) faeces and barn owl (*Tyto alba*) pellets (Newton *et al.*, 1994; Eadsforth *et al.*, 1996; Sage *et al.*, 2010). The measurement of residues in blood is also perfectly feasible (Shlosberg *et al.*, 2011), but the resources required to obtain a sufficiently large number of blood samples for analysis, particularly from live-trapped predatory birds and mammals, would be high. The detection of residues in non-destructive samples is likely to be indicative of more recent exposure, either because such samples represent concentrations in the diet eaten over a period of hours or days or, in the case of blood, because half-lives for ARs are relatively short (Vandenbroucke *et al.*, 2008).

In this chapter, we focus largely on SGARs as these are the compounds of greatest concern in terms of potential impacts on wildlife. The aims are to describe: (i) the evidence that exposure of wildlife to rodenticides does occur; (ii) the patterns and magnitudes of residues in wildlife; (iii) the main factors that drive exposure; (iv) whether exposure results in adverse effects in wildlife; and (v) the relationships between liver residues and effects in wildlife.

Evidence of Exposure of Wildlife to SGARs

A considerable number of studies have been conducted to demonstrate that the exposure of wildlife to SGARs occurs. Liver SGAR residues have been reported in wild birds and mammals from around the globe, including the USA (Stone *et al.*, 1999, 2000, 2003; Riley *et al.*, 2007; Murray, 2011; Quinn *et al.*, 2012), Canada (Albert *et al.*, 2010; Thomas *et al.*, 2011), New Zealand (Alterio *et al.*, 1997; Murphy *et al.*, 1999; Alterio and Moller, 2000), Malaysia (Duckett,

1984) and multiple European countries (Shore *et al.*, 1999; Saucy *et al.*, 2001; Kupper *et al.*, 2006; Pereira *et al.*, 2009; Berny *et al.*, 2010a,b; Vandenbroucke *et al.*, 2010; Elmeros *et al.*, 2011; Sánchez-Barbudo *et al.*, 2012). Such exposures are associated with a variety of control practices. These range from localized agricultural and urban use of SGARs (Murphy and Oldbury, 2002; Dawson *et al.*, 2003; Dawson and Garthwaite, 2003), their intensive use to protect game rearing (McDonald and Harris, 2000), the wider control of rodent outbreaks that threaten large-scale agronomic damage or pose a threat to human health through disease transmission (Hegdal and Colvin, 1988; Ramsey and Wilson, 2000; Sage *et al.*, 2008; Winters *et al.*, 2010; Coeurdassier *et al.*, 2012; Jokic *et al.*, 2012), widespread use in natural habitats to protect native fauna from invasive species (Rammel *et al.*, 1984; Murphy *et al.*, 1998a,b; Eason *et al.*, 2010) and island eradication programmes (Howald *et al.*, 1999; Thorsen *et al.*, 2000; Towns and Broome, 2003; Chapter 18).

Monitoring studies have shown that the exposure of non-target species can be both primary and secondary. Primary exposure is particularly likely among invertebrates and granivorous vertebrates. Invertebrates will feed on bait (Spurr and Drew, 1999; Dunlevy *et al.*, 2000) and detectable residues of brodifacoum have been found in insects after control operations in New Zealand (Eason and Spurr, 1995; Ogilvie *et al.*, 1997). The ingestion of soil-bound residues is another primary exposure route, although insects can also be exposed secondarily by feeding on faeces and carcasses (Eason *et al.*, 2002; Dowding *et al.*, 2010). The uptake of residues by invertebrates may also, in part, account for the accumulation of liver AR residues by insectivorous birds and mammals (Eason *et al.*, 2002; Dowding *et al.*, 2010). Non-target small mammals feeding in and around agricultural buildings during routine control operations also take rodenticide bait directly (Harradine, 1976; Townsend *et al.*, 1995; Brakes and Smith, 2005). The presence of detectable residues in some granivorous bird species (Borst and Counotte, 2002; Eason *et al.*, 2002) is also likely to be due to consumption of grain-based bait.

Secondary exposure of some predatory birds and mammal species, such as the red kite (*Milvus milvus*), buzzard (*Buteo buteo*), polecat (*Mustela putorius*) and red fox (Shore *et al.*, 1996, 1999, 2003a; Berny *et al.*, 1997; Birks, 1998; Sharp and Hunter, 1999; Kupper *et al.*, 2006; Berny and Gaillet, 2008; Walker *et al.*, 2008a; Tosh *et al.*, 2011a; Coeurdassier *et al.*, 2012) may in part or largely be due to their preying on commensal mammals that are the targets of control. However, other species that rarely feed on commensal rodents also accumulate liver residues of ARs. These include a wide range of raptors and mustelids (Berny *et al.*, 1998, 2010b; Hosea, 2000; Stone *et al.*, 2000, 2003; Walker *et al.*, 2010b; Elmeros *et al.*, 2011; Murray, 2011; Thomas *et al.*, 2011) and even species such as the Eurasian otter (*Lutra lutra*) (Fournier-Chambrillon *et al.*, 2004; Lemarchand *et al.*, 2010).

In summary, the evidence from studies from multiple continents demonstrates that non-target exposure to ARs occurs worldwide. The exposure of a broad range of predatory species with diverse trophic habits is strongly indicative of contamination of multiple food webs.

Patterns and Magnitudes of Residues in Wildlife

Residues in non-target primary consumers

Studies have been conducted on primary consumers (both target and non-target species) in and around baited areas to determine whether exposure has occurred, if it has been great enough to cause lethality and, in some cases, to assess the risk of secondary exposure and poisoning in predators. Various studies have shown that exposure and mortalities in non-target primary consumers have occurred as a result of likely primary exposure, both in vertebrate species and in invertebrates (Eason and Spurr, 1995; Ogilvie *et al.*, 1997; Spurr and Drew, 1999; Pain *et al.*, 2000; Brakes and Smith, 2005).

It is apparent from these studies that the extent of exposure can vary markedly between species. For example, wood mice (*Apodemus sylvaticus*) appear to be more likely to be exposed to ARs than bank voles (*Myodes glareolus*) and, particularly, field voles (*Microtus agrestis*) (Cox and Smith, 1990; Brakes and Smith, 2005). This is consistent with differences between the species in their diets; wood mice are generalists, although seeds make up a large proportion of their diet, whereas voles are more herbivorous and field voles largely only eat grasses (Harris and Yalden, 2008). Wood mice are also habitat generalists, highly mobile and will enter buildings (Harris and Yalden, 2008) and they are, therefore, probably also more likely to encounter baits than some other species. This mobility also means that wood mice with detectable AR residues have been found at distances of up to 200 m from baited areas (Townsend *et al.*, 1995; Tosh *et al.*, 2012). Given the mobility of this species in agricultural landscapes (Tattersall and Macdonald, 2003), it is likely that wood mice act as vectors of AR residues, 'exporting' them probably hundreds of metres, and possibly kilometres, away from baiting areas.

The proportion of wood mice exposed to ARs during baiting campaigns on farms has been found to be 50–70% (Brakes and Smith, 2005), 20–30% (Townsend *et al.*, 1995) and 15% (Tosh *et al.*, 2012). This variability most likely reflects differences between studies in a number of factors, such as timing, pattern, spatial extent and intensity of both baiting and trapping, together with the methodology used to quantify exposure (Townsend *et al.*, 1995; Tosh *et al.*, 2012). AR residues are rarely, if ever, measured in non-target primary consumers but, some 6–10 weeks after the onset of baiting, liver SGAR residues were found to range between not detected and 0.681 mg kg^{-1} in wood mice sampled from across 16 farms (Tosh *et al.*, 2012).

In general, data on whole body residues from typical baiting campaigns are needed to gauge the likely risk of secondary poisoning in predators (Luttik *et al.*, 1999). The lack of such data, and of any associated understanding of how residue accumulation in non-targets varies spatially and temporally in relation to baiting, has hampered assessment of the likely risk of secondary exposure and poisoning in predators.

Residues in predatory and omnivorous species

In comparison with studies on small mammals, the measurement of AR residues in predatory and omnivorous birds and mammals is better documented. Exposure is often assumed to be secondary, but may be a mixture of primary and secondary, particularly for omnivorous species. Recent studies of exposure associated with the normal agricultural use of ARs have revealed widespread, but predominantly low-level, accumulation of AR residues in predatory and omnivorous species, with a small percentage of individuals having relatively high liver concentrations. For example, in Britain, the Predatory Bird Monitoring Scheme, or PBMS (Walker *et al.*, 2008a), undertakes long-term analysis of the exposure of barn owls to SGARs. Of 204 barn owls examined between 2007 and 2010, 174 (85.3%) contained detectable liver residues of one or more SGAR (Fig. 17.1a). The sum SGAR concentration ranged between 0.002 μg g^{-1} wet weight and 0.73 μg g^{-1} wet weight but was below 0.05 μg g^{-1} wet weight in approximately 70% of those birds with detected residues (Fig. 17.1b). A broadly similar scale and pattern of exposure has been reported in stoats (*Mustela erminea*) and weasels (*Mustela nivalis*) from Denmark (Elmeros *et al.*, 2011), red foxes and European hedgehogs (*Erinaceus europeaus*) from the UK (Dowding *et al.*, 2010; Tosh *et al.*, 2011a), and various predatory bird species in Canada and the USA (Murray, 2011; Thomas *et al.*, 2011).

It is possible that the monitoring of animals that have died either from any cause or predominantly from causes unrelated to poisoning (for example collisions with cars) is likely to underestimate exposure. This is because poisoned animals may tend to die

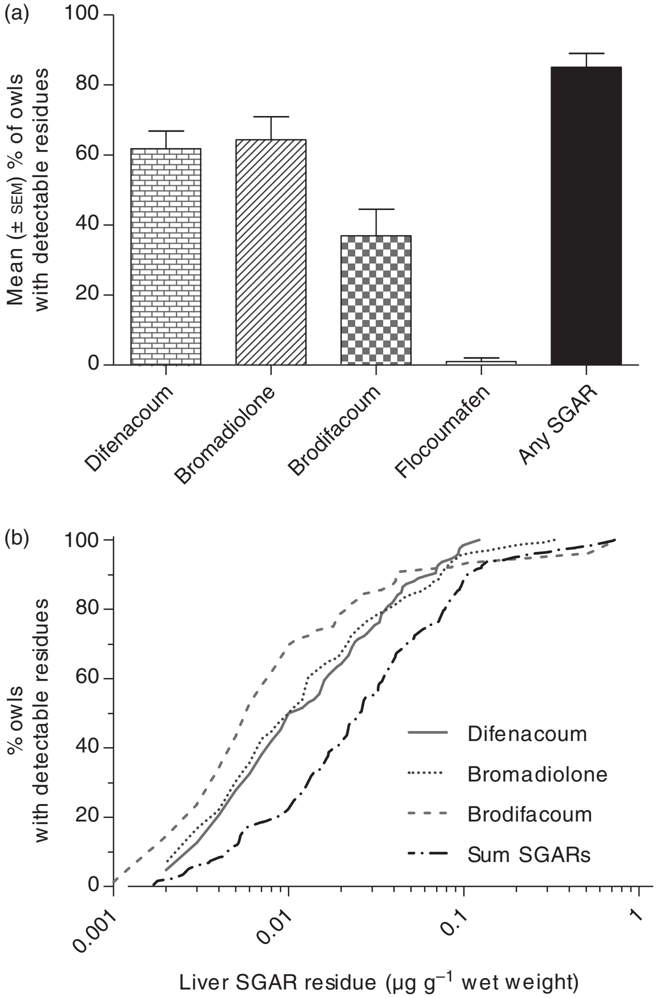

Fig. 17.1. (a) Data from the Predatory Bird Monitoring Scheme (PBMS) in Britain for the mean (±SEM) annual proportion of barn owls (*Tyto alba*) found dead with detectable liver residues of the second-generation anticoagulant rodenticides (SGARs) difenacoum, bromadiolone, brodifacoum, flocoumafen and one or more of those compounds (any SGAR). Data are from 4 years (2007–2010) and between 49 and 53 owls were examined each year. (b) Cumulative frequency of the liver SGAR concentrations in those owls with detectable residues. Data are presented by compound and as the sum concentration of all SGARs present in the liver.

out of sight in their roosts or dens and so not be included in samples collected for analysis. However, acute exposure to ARs can result in altered behaviour in rodents (Cox and Smith, 1990, 1992; Brakes and Smith, 2005), and it has been speculated that exposure to rodenticides may alter behaviour or physiology in a manner that predisposes individuals to being killed by other factors; this could lead to overestimates of exposure, as measured by residues, for the population as a whole. The extent to which either bias occurs, if at all, is unknown.

The high percentage (typically in excess of 70%) of animals with detectable residues reported in recent studies contrasts with the lower values reported in earlier investigations, often on the same species (for example, see: Shore *et al.*, 1996, 2003b; McDonald *et al.*, 1998; Newton *et al.*, 1999; Walker *et al.*, 2008b). This difference partly, if not largely, reflects changes in analytical sensitivity. In earlier studies, residues were normally quantified in the liver and other tissues using high performance liquid chromatography (HPLC) with fluorescence detection. More recent studies have used liquid chromatography–mass spectrometry (LCMS) techniques, which have improved analytical detection limits and have a greater certainty of compound identification based on ion mass. The result is that low-level residues that were previously undetected by the HPLC method are now quantified, as has been demonstrated when the same tissues were quantified by both methods (Dowding *et al.*, 2010). This change in analytical methodology means that care has to be taken when comparing data from different studies or time periods. Either the analytical methods, and hence the sensitivity of the measurements, need to be similar for different studies, or data must be normalized to take account of such differences (Tosh *et al.*, 2011a).

One other characteristic typical of residues in predatory birds and mammals in areas where multiple compounds are used is that multiple residues are detected in the liver. In all, 119 of the 204 barn owls examined by the PBMS between 2007 and 2010 contained residues of either two or three SGARs in the liver; this was 68% of the 174 birds with detectable residues. Between 23 and 59% of foxes from the UK, 23% of European hedgehogs from Britain, 79% of stoats and weasels from Denmark, and 40% and 29% of great horned owls (*Bubo virginianus*) and red-tailed hawks (*Buteo jamaicensis*), respectively, from Canada contained multiple compounds. The presence of multiple compounds in the livers of predators has been thought to be indicative of multiple exposure events, as individual prey items were most likely to have been exposed to a single compound used for rodent control in their home range. However, a recent study on wood mice in an agricultural landscape found that multiple compounds were common in three out of eight animals that had detectable residues, and that some animals contained compounds not used on the farms where they were captured (Tosh *et al.*, 2012). This suggests that wood mice forage across multiple farm holdings that use different compounds. In addition, minor cross-contamination was detected in some baits and this may also contribute to multiple compounds being present in mice, and subsequently in predators. Thus, the presence of multiple compounds in predators may be indicative, but is not diagnostic, of multiple exposure events.

On a broad scale, the overall pattern (relative occurrence of different compounds) of wildlife exposure to SGARs tends to reflect usage. In Britain, difenacoum and bromadiolone are the most commonly used SGARs, whereas brodifacoum and flocoumafen, restricted to indoor use only, are applied much less widely (Garthwaite *et al.*, 1999; Dawson *et al.*, 2003). This preponderance towards difenacoum and bromadiolone usage is reflected in the relative frequency with which different SGARs are detected in barn owls (Fig. 17.1) and in other species (Dowding *et al.*, 2010). In contrast, flocoumafen and brodifacoum are more widely used in Northern Ireland than in Britain (Tosh *et al.*, 2011b), and this is again reflected in the residues accumulated by wildlife. Brodifacoum and flocoumafen were detected relatively more frequently in the livers of foxes from Northern Ireland than in the livers of foxes collected over the same time period from Scotland, England and Wales (Tosh *et al.*, 2011a).

Although liver residues in wildlife do indicate the relative scale of use of different ARs, some care is needed when inferring information on exposure from tissue residues. This is because tissue half-lives vary between the anticoagulants. In addition, more persistent (and toxic) ARs can displace less persistent compounds from liver-binding sites. Brodifacoum, in particular, has a longer half-life than most other compounds in house mice at least (Vandenbroucke *et al.*, 2008) and, as a result, liver residues of this compound may persist for longer, thereby increasing the likelihood that they will be detected in monitoring programmes.

There is some evidence of this from the exposure data collected on barn owls in Britain. The numbers of barn owls observed to have detected residues of each compound can be compared with the number that would be expected to have detectable residues given the relative frequency of use on farms of different SGARs. When this was done for barn owls that died between 1995 and 2002, a period roughly contemporaneous with the most recent data available on SGAR usage in Britain (Garthwaite *et al.*, 1999; Dawson *et al.*, 2003), the numbers of owls with detected residues of difenacoum and bromadiolone were up to twofold lower than expected, but the number with brodifacoum residues was fivefold higher than expected (Table 17.1). When the analysis was repeated for owls that died between 2007 and 2010 and that had been analysed with the more sensitive LCMS methodology, the picture was somewhat changed. More owls were observed to have residues than expected for all compounds. This is perhaps not surprising as owls are likely to hunt over multiple farms and to acquire more residues than would be predicted simply from the number of farms using rodenticides; the likely reason why this was not evident in the 1995–2002 cohort of owls is because low-level residues went undetected. More importantly, though, the difference between the observed and expected numbers of contaminated owls was by far the most marked for brodifacoum (Table 17.1). This again is consistent with brodifacoum residues persisting for long periods of time, and so tissue residues are likely to over-represent usage compared with other compounds.

Key Factors Mediating the Accumulation of Liver Residues

While the exposure of predatory birds and mammals to SGARs is widespread, there is significant inter-species variation in the accumulation of liver residues, both in terms of the proportion of animals with detectable residues and the magnitude of the content of those residues (Fig. 17.2). The studies from which the data in Fig. 17.2 are drawn all used the older, less sensitive HPLC techniques and there are, to date, too few studies using the newer LCMS techniques to make a similar comparison – although it is likely that the use of LCMS analysis will show that most individuals

Table 17.1. Numbers of farms using the second-generation anticoagulant rodenticides (SGARs) difenacoum, bromadiolone, brodifacoum and flocoumafen in Great Britain and the observed and expected frequency of occurrence of residues in barn owls (*Tyto alba*) that died between 1995 and 2002, and between 2007 and 2010. Data on residues in birds are from the Predatory Bird Monitoring Scheme (PMBS). (R.F. Shore, unpublished data.)

	Difenacoum	Bromadiolone	Brodifacoum	Flocoumafen	No SGARs
Estimated number of arable, grass and fodder crop farms using each rodenticide (% of all farms)[a]	41,010 (48%)	22,229 (26%)	1748 (2%)	428 (0.5%)	20,748 (24%)
Observed no. barn owls (1995–2002) with residues	108	75	43	5	272
Expected no. barn owls (1995–2002) with residues[b]	211	114	9	2	107
Observed no. barn owls (2007–2010) with residues	126	132	76	3	30
Expected no. barn owls (2007–2010) with residues[b]	97	53	4	1	49

[a]Data from Garthwaite *et al.* (1999) and Dawson *et al.* (2003).

[b]Expected numbers of owls with residues are estimated on the basis of the numbers of farms using each type of rodenticide. Differences between observed and expected numbers are significant for both cohorts of owls (chi-squared test: $\chi^2 \geq 41.7$; df = 3; $P < 0.0001$ in both cases).

contain some AR liver residues, albeit at low levels. In future, comparisons between species may need to focus on differences in the frequency distribution of residue magnitudes rather than on the presence or absence of residues.

There are four major factors that are likely to mediate the accumulation of residues by wildlife, namely diet, usage, rodenticide resistance and physiology.

Diet and dietary habit have long been assumed to be a major explanatory factor for inter-species variation in exposure. Scavenging species may be especially at risk because they feed on carcasses that could include animals poisoned by ARs; hence, studies on non-target exposure associated with large-scale baiting activities have focused on species such as the buzzard and the fox (see, for example: Berny *et al.*, 1997;

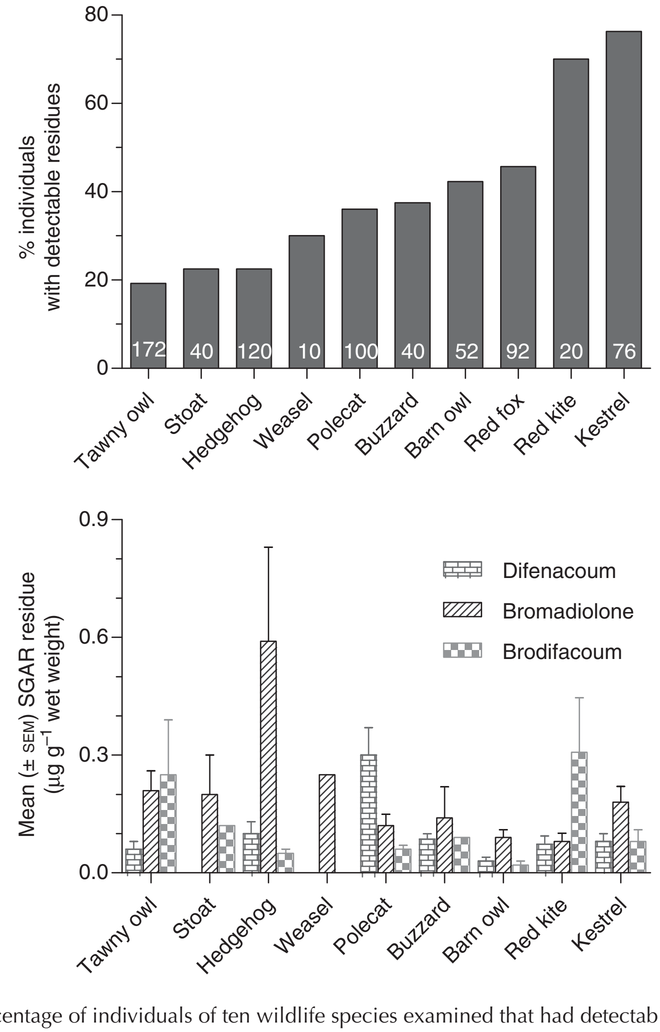

Fig. 17.2. (a) Percentage of individuals of ten wildlife species examined that had detectable liver residues of one or more second-generation anticoagulant rodenticides (SGARs) or the first-generation anticoagulant rodenticide coumatetralyl, as measured by high-performance liquid chromatography (HPLC) with fluorescence detection. (b) Mean (±SEM) liver concentrations of three SGARs reported for those species. Data for both graphs are from various studies as summarized by Dowding *et al*. (2010) and, in the case of the red kite and buzzard, from Shore *et al*. (2000, 2006).

Berny and Gaillet, 2008). The red kite is also a focal species of concern, partly because it is known to scavenge rat carcasses (Carter, 2001). However, the effect of diet on mediating exposure has rarely actually been demonstrated. Furthermore, significant differences in residue accumulation occur between species such as the tawny owl (*Strix aluco*), barn owl and kestrel (*Falco tinnunculus*) (see Fig. 17.2), despite the similarity of the diets of these species; the causes of such differences are unclear.

A recent study does indeed provide some field evidence that diet is a key factor in some circumstances. The accumulation of liver SGAR residues was compared between red foxes from Northern Ireland and foxes from the rest of the UK (Tosh *et al.*, 2011a). The prey guild in Northern Ireland is restricted compared with the rest of the UK, as field voles, common shrews (*Sorex araneus*) and bank voles are absent or restricted in their distribution (Harris and Yalden, 2008). Foxes in Northern Ireland eat more wood mice and commensal rodents than foxes in Britain (Fairley, 1970; Robertson and Whelan, 1987). Liver SGAR residues were generally more prevalent in foxes from Northern Ireland than from elsewhere and this was attributed, in part, to the restricted prey guild. Similarly, there is some evidence to suggest that the exposure of barn owls to SGARs in Britain is positively related to the proportion of wood mice in their diet, with barn owls from regions where they feed more extensively on wood mice (Love *et al.*, 2000) tending to have a greater prevalence of liver SGAR residues (R.F. Shore, unpublished data).

Usage is also likely to influence exposure and the associated accumulation of residues; SGAR residues are only typically found in wildlife in the general areas where the compounds are used. Understanding the nature of the relationship between exposure and usage is important if restrictions on use are to be considered as one way to mitigate non-target exposure. The most basic question is whether the exposure of non-target species increases with increased usage? Surprisingly, this question is not readily answered, probably because it requires large-scale analysis of residues in wildlife across large regions where usage varies. It is possible, though, to address this question using the long-term data from the PBMS for Britain. A breakdown of the agricultural usage of SGARs by country in the UK indicates that SGAR use is typically greater in England than in Wales or Scotland, based on the most recent data available, which date back to the year 2000 and earlier (Garthwaite *et al.*, 1999; Dawson *et al.*, 2003). The frequency of occurrence of SGAR liver residues in barn owls from each country that died between 1990 and 2010 was likewise lower in Scotland and Wales than in England, although the numbers of owls from Wales and Scotland are relatively small (Fig. 17.3). In contrast, liver SGAR residues were found to be just as, if not more, prevalent in polecats from Wales as in animals from two regions of England (Shore *et al.*, 2003a). Thus, the link between total amount of usage and exposure of wildlife at regional scales is somewhat equivocal.

On a local scale, the relationship between amount of rodenticide use and the extent of non-target exposure is likely to be more complex and particularly influenced by the way that rodenticides are applied. Practices such as lack of protection of bait stations, broadcast baiting, permanent baiting or failure to remove bait at the end of baiting campaigns, and failure to remove the carcasses of poisoned rodents, are all likely to increase the risk of primary and secondary exposure of non-targets. Such practices, or the lack of them, may be more important than the total amount of compound used. There was no spatial relationship between the scale of what was, on occasion, massive use of SGARs on infected farms during the foot-and-mouth disease outbreak in Britain in 2001 and the prevalence of liver SGAR residues in barn owls and buzzards (Shore *et al.*, 2006). Contrary to expectations, liver difenacoum residues were, if anything, less prevalent in barn owls from areas with foot-and-mouth disease. It was considered that this was likely to have been because there were stringent measures to reduce non-target exposure on infected farms and also because activities by others, such as gamekeepers who use

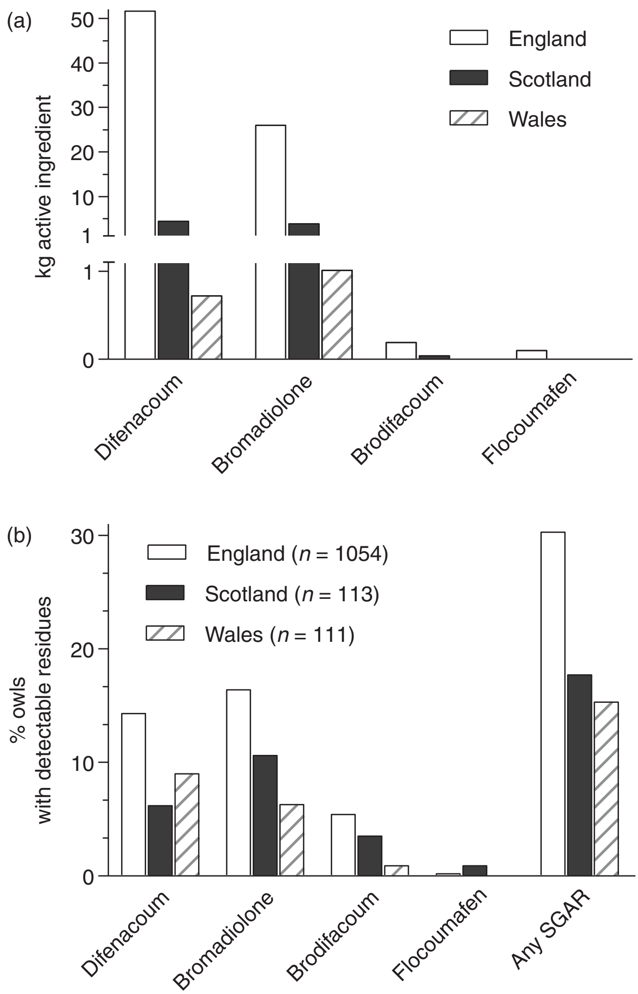

Fig. 17.3. (a) Amount of SGAR used (kg active ingredient) in England, Scotland and Wales. Data are from Pesticide Usage Survey Reports (Garthwaite *et al*., 1999; Dawson *et al*., 2003). (b) Percentage of barn owls from England, Scotland and Wales found dead between 1990 and 2010 that had detectable concentrations of the second-generation anticoagulant rodenticides (SGARs) difenacoum, bromadiolone, brodifacoum, flocoumafen and one or more of those compounds (any SGAR). Data are from the Predatory Bird Monitoring Scheme, or PMBS (R.F. Shore, unpublished data).

rodenticides extensively (McDonald and Harris, 2000), stopped. So the way that SGARs are used, rather than total amount used, is likely to be of prime importance and is probably an important means of reducing non-target exposure.

Resistance to first-generation anticoagulants and cross-resistance to certain SGARs (difenacoum and bromadiolone) has developed among commensal rodents (see, for instance: Grandemange *et al*., 2010; Baert *et al*., 2012; Endepols *et al*., 2012; Pelz *et al*., 2012; Buckle, 2013b). Resistance is potentially a major factor that could affect the scale of secondary exposure in some predators (see Chapter 16). This is for two main reasons. The first is that resistant rats may accumulate significantly greater body burdens of rodenticide than non-resistant rats. Laboratory studies in which resistant and non-resistant rats were experimentally given difenacoum bait found that body burdens were on average 30–40% higher in resistant than non-resistant animals (Atterby *et al.*, 2005), though the differences between the two rat groups were not statistically significant. The second is that resistant rats are likely to survive, and so be available for capture, longer than non-resistant individuals. This may enhance the potential for secondary exposure of predatory species but is less likely to have an impact on scavengers. The importance of resistance in mediating exposure and the resultant risk of secondary poisoning is currently unknown, and is a key question given the likely future geographical spread of resistance to SGARs.

Although the measurement of tissue residues is often used as a proxy for exposure, these figures are not a direct measure. Differences in nutritional plane (for instance in dietary vitamin K intake) and in the pharmacological handling and metabolism of rodenticides will affect both the assimilation of SGAR residues and the likelihood of adverse effects. Physiology is potentially one of the most important factors affecting uptake and effects, as is suggested by the large interspecies differences in acute toxicity (WHO, 1995; Eason *et al.*, 2002; Rattner *et al.*, 2011), so potential species differences in physiology need to be borne in mind when interpreting the significance of residues in wildlife.

Relationships Between Liver Residues and Effects in Wildlife

Acute mortality

Acute mortality is the major effect that has been examined in relation to SGAR residues in wildlife. Diagnoses that an AR has caused mortality are usually based on post-mortem evidence of haemorrhage that is not associated with other signs of trauma, together with the chemical detection of AR residues in body tissues, usually the liver, but such diagnoses can be difficult. Carcasses with no detected AR residues often have some signs of haemorrhage. This may either occur post-mortem or be associated with minor but unknown trauma. Conversely, haemorrhaging caused by anticoagulants may be microscopic and only detectable by histological examination (Rattner *et al.*, 2011); for example, if there is minor but fatal haemorrhaging within the brain tissue. Thus, neither the absence nor the detection of haemorrhaging is definitively diagnostic of AR poisoning. Likewise, the presence or absence of measured residues in the body is not diagnostic of AR poisoning. In some studies, analytical measurements have been confined to specified ARs, but not to all of the ARs to which animals may have been exposed, and death may have been caused by a compound not in the analytical menu. In any case, the presence of residues is indicative only of exposure, not necessarily of poisoning. Despite these difficulties in diagnosis, samples of animals that have died from any cause have been examined to determine what proportion is believed to have been killed by ARs. Typically, this proportion is less than 10% (see, for example: Stone *et al.*, 2003; Berny and Gaillet, 2008; Murray, 2011), although such figures are generally thought to represent a minimum because, as discussed earlier, poisoned animals may die out of sight or be quickly scavenged, and so be under-represented in any sample.

Because liver residues are often measured in wildlife, there has been interest in whether these can be used as a diagnostic of poisoning. However, the relationship between the magnitude of liver residues and likelihood of mortality is poorly defined, partly because of the difficulties in making definitive diagnoses of rodenticide poisonings. Sometimes, a liver concentration of >0.1–0.2 mg kg^{-1} wet weight has been used to indicate that animals may have been at risk from poisoning (for instance see Maltby, 2008), though this was, in fact, only originally proposed as a ‘potentially lethal range’ of SGARs for barn owls. The range was defined on the basis that: (i) the free-living barn owls that were diagnosed as poisoned by SGARs from post-mortem signs of haemorrhage had liver concentrations >0.1 mg kg^{-1} wet weight; and (ii) barn owls that died after laboratory exposures had liver residues of 0.2–1.72 mg kg^{-1} wet weight (Newton *et al.*, 1998, 1999). This potentially lethal range is not diagnostic, as many barn owls with residues >0.2 mg kg^{-1} wet weight die from causes other than AR poisoning (see, for example, Walker *et al.*, 2010a,b). The range may also vary for different ARs and probably cannot be directly extrapolated to other species because of the known large inter-species variation in sensitivity. Indeed, brodifacoum residues as low as 0.01–0.03 mg kg^{-1} wet weight have been reported to be associated with mortalities in great horned owls (Stone *et al.*, 1999, 2003).

A recent study has used probabilistic methods to assess the likelihood that any given AR residue is associated with mortality (Thomas *et al.*, 2011). This analysis indicated that the probability of death in barn owls with a liver SGAR residue of 0.1 mg kg^{-1} wet weight was 11% and rose to 22% for barn owls with liver residues of 0.2 mg kg^{-1} wet weight. These analyses therefore suggest that there are likely to be mortalities below the 'potentially lethal range' proposed for this species. Comparison of data for different species also indicated that the likelihood of mortality associated with any given residue varies significantly between wildlife species.

Chronic effects

It is possible that sublethal exposure to ARs and the accumulation of residues may result in sublethal effects in wildlife. Changes in behaviour associated with exposure to ARs (Cox, 1991; Littin *et al.*, 2002; Brakes and Smith, 2005) could potentially impair survival, but the occurrence of such impacts at an ecologically significant level has not been demonstrated, nor have such effects been linked to known intakes or tissue residues. ARs can also affect bone metabolism. Bone contains three vitamin K-dependent proteins and AR therapy in humans can reduce bone mass, density and strength (WHO, 1995; Barnes *et al.*, 2005). Whether there are any effects of sublethal exposure to ARs on bone in wildlife species is unclear, but there was no association between bone breaking strength or density and liver SGAR residues in sublethally exposed barn owls and kestrels. The liver brodifacoum, difenacoum and bromadiolone concentrations in the birds tested ranged from 0.012 to 0.238 mg kg^{-1} (brodifacoum), 0.003 to 0.336 mg kg^{-1} (difenacoum) and 0.013 to 0.581 mg kg^{-1} (bromadiolone) wet weight (Knopper *et al.*, 2007).

A number of other chronic effects have been associated with sublethal exposure to ARs in wildlife. This includes reproductive toxicity, but studies are equivocal in their results in that some studies have demonstrated adverse effects, while others have not (WHO, 1995; Robinson *et al.*, 2005), and doses were sometimes sufficient to cause adult mortality. There have also been some reports of sublethal haemorrhaging, liver damage and weight loss associated with exposure to ARs (Oliver and Wheeler, 1978; Robinson *et al.*, 2005). Such sublethal effects might be expected to be directly related to the acute mode of toxicity of ARs and transient exposure, with animals either recovering or dying if exposure was sustained.

Several recent field studies suggest that there may be chronic, indirect effects associated with the accumulation of sublethal tissue AR residues. There was a negative relationship between body condition and the magnitude of AR residues in a sample of 130 stoats and weasels in Denmark (Elmeros *et al.*, 2011), in which mean accumulated liver AR residues varied between 0.009 mg kg^{-1} wet weight (flocoumafen in stoats) and 0.272 mg kg^{-1} wet weight (bromadiolone in weasels). No such negative association was apparent in the same species in Britain (McDonald *et al.*, 1998), but sample size and the proportion of animals with detected residues were both smaller and the power of the study to detect any associations may have been poor. There have also been reports of positive associations between pathogens and the accumulation of residues of chlorophacinone (a first-generation AR) in rodents (Vidal *et al.*, 2009), and between the incidence of notoedric mange in bobcats and mountain lions (*Puma concolor*) and their accumulation of (mostly second-generation) AR residues (Riley *et al.*, 2007). The association between mange and ARs was statistically significant for bobcats with relatively low total liver AR residues (animals with residues greater than 0.05 mg kg^{-1} wet weight). Overall though, the significance of the findings of these different studies is difficult to interpret (Riley *et al.*, 2007). This is partly because there is no established toxic mechanism that accounts for interactions between disease and exposure to ARs, and also because the results are correlative rather than indicating causal effect; the association between disease and ARs may simply be coincidence. It may also be that diseased animals are weakened and more likely to forage in suboptimal areas, such as areas close to human habitation, where ARs are likely to be more widely used.

Conclusions

Monitoring liver residues in wildlife has provided key information about the extent of non-target exposure and a means of quantifying the success of mitigation measures designed to limit non-target exposure. Careful analysis of the data on liver residues in wildlife has also helped to explain which factors are important in mediating the exposure of non-target species. There are perhaps three main areas where progress is likely in the near future, or is urgently needed.

The importance of resistance in target species in terms of mediating secondary exposure and poisoning in non-targets is unquantified. This remains a key question, given the spread of resistance to SGARs (Kerins *et al.*, 2001; Lodal, 2001; Pelz, 2007; Vein *et al.*, 2011; Buckle, 2013b), and has been difficult to resolve because of the logistical difficulties in detecting and mapping resistance over large areas. However, the genetic mutations responsible for resistance are now better characterized (Rost *et al.*, 2009), and the presence of the genes responsible for resistance can be identified from tail tip samples using relatively high-throughput molecular techniques (Pelz *et al.*, 2007). This presents the possibility of generating detailed maps of the presence and prevalence of resistance (see Chapter 9). Such spatial data can be coupled with the measurement of AR residues in non-target species and the monitoring of mortality incidents to determine whether there is an association between resistance and the secondary exposure and poisoning of non-targets.

The probabilistic assessment of the likelihood of mortality associated with liver SGAR residues (Thomas *et al.*, 2011) is a potentially exciting development which may have a major impact on how monitoring studies are reported. This is because such approaches have the potential, for the first time, to estimate likely minimum toxicity at a population level. This will aid the interpretation of whether such mortality is ecologically significant. Probabilistic approaches to analysing residue data may also help to identify which wildlife species are inherently more sensitive to rodenticides; these will be species with a high probability of mortality associated with accumulation of relatively small amounts of liver residues. It is difficult to see how such comparative toxicity information can be gathered in any other way as experiments on wild species rely on the use of small numbers of captive individuals or colonies of a small number of species (Newton *et al.*, 1994; Rattner *et al.*, 2010, 2011). Wide-scale testing on multiple species would not be practical or ethically justifiable. However, probabilistic approaches to assess the significance of residues are subject to various potential biases and will rely on the availability of good field residue measurements and, in particular, on the careful characterization of residues in individuals known to have died from AR poisoning. Further work is needed to develop these approaches and, especially, their applicability in complex scenarios where exposure to multiple compounds is commonplace.

Finally, the question as to whether there are significant sublethal effects in non-target species remains a burning issue, particularly given the widespread nature of sublethal exposure in non-target species throughout the world. The number of studies linking sublethal effects to exposure is slowly growing, but all suffer from the same problem of being correlative. Future field studies that quantify exposure to ARs should, where possible, also assess the disease and general health status of animals. This may increase the weight of evidence as to whether sublethal exposure to rodenticides does cause significant effects, although any such studies will still be correlative in nature. Laboratory experiments on model organisms are also needed to demonstrate if there is causality between exposure and susceptibility to disease and to elucidate any underlying mechanisms. Such experiments are difficult to accomplish and pose a significant challenge for the future.

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18 Rodent Control and Island Conservation

G. Howald,[1] J. Ross,[2] and A.P. Buckle[3]
[1]*Island Conservation, Santa Cruz, California, USA;* [2]*Faculty of Agriculture and Life Sciences, Lincoln University, Lincoln, New Zealand;* [3]*School of Biological Sciences, University of Reading, Reading, UK*

Introduction

On 15 June 1918, the SS Mokambo ran aground on Lord Howe Island in the south-west Pacific (Long, 2003). There was little loss of life; that came later. The ship was infested with ship rats, *Rattus rattus*, and these went ashore with the human survivors while the ship was temporarily beached. In the years that followed, rat predation resulted in the extinction of at least five species of the island's endemic birds, including the Robust white-eye (*Zosterops strenuus*) and Lord Howe Island thrush (*Turdus poliocephalus vinitinctus*), and the serious decline of the populations of many others. A variety of other taxa was also affected, including molluscs, insects and amphibians. Another recent event was the devastation caused by the arrival of roof rats on Big South Cape Island, New Zealand, in the early 1960s, when several endemic birds species were quickly extirpated (Thomas and Taylor, 2002). We know of these extinctions because they occurred when accurate faunal records were available. However, such events have occurred in all of the world's oceans for thousands of years, resulting in the extinction of many species, which we now only know from the fossil record, or not at all. The immense impact of alien rodents on the faunas of oceanic islands continues to this day (Blackburn *et al*., 2007; Varnham, 2010).

Such impacts have been long recognized. In 1958, Charles Elton described the effects of alien invasives on island ecosystems as 'one of the great convulsions of the world's fauna and flora' (Richardson and Pýsek, 2007). Modern ecologists are no less alarming in the words used to describe this phenomenon, with impacts on biodiversity described, for example, as 'immense, insidious and usually irreversible' (Veitch and Clout, 2002). The spread of invasive rodents has been well documented (Atkinson, 1985; Long, 2003). The main species involved are the Norway rat (*Rattus norvegicus*), roof rat (*R. rattus* – aka the ship, house or black rat), the house mouse (*Mus musculus/domesticus*) and the Polynesian rat or kiore (*Rattus exulans*). The first three species originated in Asia and had become widely distributed, via terrestrial routes, before spreading from Europe to the world's oceanic islands during the period of European ship-borne exploration and subsequent migration. The Polynesian rat was also native to the Indo–Malayan region and is thought to have been spread across the Pacific by the Polynesian peoples, and their ancestors, reaching the Hawaiian islands by 800 AD (Atkinson, 1985).

The most well-known impact on native faunas of rodent aliens is, of course, predation, because this is most readily observed and identifiable. Other less obvious impacts may be equally important, such as competition for food resources and nest sites. There are certainly even more subtle effects, for example the prevention of vegetal regrowth caused by seed depredation. This may result in broad impacts on a wide variety of taxa, through changes to the composition of native flora, but may go largely unnoticed in short-term studies. Courchamp *et al.* (2003) examined the extensive range of impacts, both obvious and insidious, of mammalian invasives on islands, including those of rodents. There is no room for doubt that any rodent species introduced as an alien to an oceanic island will have an important impact on the island's biodiversity. In many cases, the effects will be catastrophic, as clearly recorded by Atkinson (1985) and Courchamp *et al.* (2003). These impacts are often accelerated because endemic faunas have developed no behavioural mechanisms to protect themselves from small ground predators, as seen in dramatic form in the consumption of live albatross chicks by house mice on Gough Island (Cuthbert and Hilton, 2004).

Almost as soon as the adverse impacts of alien rodents on islands were recognized, conservationists began projects to mitigate, or even reverse, their effects. Fortuitously, this enlightenment coincided with the invention and development of the anticoagulant rodenticides (Chapter 6). These compounds have been the mainstay of projects for both the long-term management and total removal of rodents from islands. One of the first such projects to use rodenticides was that carried out on Nonsuch Island in the Caribbean to protect the Bermuda petrel (*Pterodroma cahow*) (Wingate, 1985). All subsequent projects have followed a similar pattern, although methods have differed in detail.

Essentially, there are two principal strategies for the management of alien rodents. The first, eradication, is employed on relatively small islands where logistics permit this approach. The size of islands that are capable of having the eradication strategy applied is steadily growing as new rodenticide application techniques are employed (Brooke *et al.*, 2007). The advantage of this approach is obvious in that benefits are long term, provided that rodents do not return to the islands from which they have been removed. Where logistics, particularly the size of islands, prevents eradication, a second approach, long-term rodent management, is adopted. This has the disadvantage that action is required on an ongoing basis, but many such projects are now in place around the world (see, for example: Coulter *et al.*, 1985; Zino *et al.*, 2001).

In this chapter, we describe the impacts of alien invasive rodents on natural ecosystems, with emphasis on oceanic islands, and review management techniques to mitigate their effects.

Island Invasions by Rodents

Most rodent species are highly adapted, *r*-selected, boom-or-bust strategists (see Chapter 1). Such pre-adaptation to invasiveness allows them quickly to take advantage of abundant new resources and is why rodents are among the most successful mammalian colonizers of islands. Atkinson (1985) reported that 82% of the world's 123 major islands and island groups were inhabited by one or more of the common commensal rodent species. Colonization continues at the rate of almost six islands every two decades (Russell *et al.*, 2007a). Undoubtedly, rodents are able to colonize islands without human assistance. The swimming abilities of some species are well known; Norway rats, for example, are capable of swimming distances of up to 1 km (Russell *et al.*, 2008b). However, the ability of rodents to colonize oceanic islands that were distant from naturally populated land masses came only with the assistance of human seaborne movement.

It is thought that the earliest substantial human-mediated movement of rodents began around 1500 BC with the colonization of the islands of the western Pacific by the Lapita peoples, who transported Polynesian rats with them wherever they settled, by accident or intention (Atkinson, 1985). The translocation of *R. exulans* continued across the Pacific with the true Polynesian peoples, and by 1000 AD these rats, and their human vectors, had reached the islands of New Zealand, Easter and Hawaii. Polynesian rats are the smallest of the common colonizing rat species and are thought to be less damaging than Norway and ship rats. They have also been a part of the ecosystems that they now inhabit for so long that some argue that ecological equilibrium has been reached. Nevertheless, recent studies on Henderson Island in the Pitcairn group, for example, confirm the severe ongoing impacts of Polynesian rats on the island's population of Henderson petrel (*Pterodroma atrata*) and other seabirds (Brooke *et al.*, 2004). An eradication programme is now planned. There is no doubt that the impacts of Polynesian rats on the ecosystems of this Pacific island have been extremely severe and continue to this day.

The other three commensal rodent species that now colonize islands worldwide all spread from the Indo–Asian land mass. The first species involved was *R. rattus*. This was the main rat pest in Europe throughout the Middle Ages and was on board the ships of the first European explorers of that time. Consequently, many of the islands of the Atlantic and Indian oceans were colonized in the 'Age of Discovery' during the period 1500 to 1700 AD (Atkinson, 1985). European excursions into the Pacific were rare at that time, and this probably explains why few islands were then inhabited by ship rats. Norway rats appear to have reached Europe very soon after 1700 AD and, because this event is relatively recent, records of their spread are probably reasonably accurate (Long, 2003). Not only did Norway rats displace ship rats as the principle European rodent pests on land but, importantly for island colonization, they replaced them on ships as well. Consequently, from 1700 onwards, there was a rapid expansion in the numbers of islands around the world that were infested with Norway rats. House mice originated in central Asia but, probably because of their diminutive size, less is known about the chronology of their invasions of islands. What little is known is documented by Long (2003). Atkinson (1985) reviewed the distributions of the three rat species among the islands of the Atlantic, Pacific and Indian oceans, and the current situation has not changed much since that time (Table 18.1). Long (2003) provides detailed information on the distribution of these alien invasives.

Although not strictly a rodent, mention should also be made of the European rabbit (*Oryctolagus cuniculus*). This species has been purposely transported to more than 800 islands worldwide (Long, 2003). Because of its herbivorous food habits, it does not predate native fauna, but its impacts on native floras are very profound, with consequent catastrophic effects on endemic faunas (Courchamp *et al.*, 2003). The methods

Table 18.1. Distribution of commensal rats (*Rattus* spp.) among major islands and island groups. (From Atkinson, 1985.)

	Number of islands or island groups			
Rat species present	Pacific Ocean	Indian Ocean	Atlantic Ocean	Total
R. exulans alone	2	–	–	2
R. norvegicus alone	4	1	5	10
R. rattus alone	6	17	3	26
R. exulans + *R. rattus*	7	–	–	7
R. exulans + *R. norvegicus*	6	–	–	6
R. rattus + *R. norvegicus*	4	4	5	13
All three species	15	–	–	15
One or more unidentified commensal rat species present	9	7	6	22
Free of/probably free of commensal rodents	12	5	5	22
Total	65	34	24	123

of dealing with rodents on islands, which will be explored in the remaining sections of this chapter, can with some appropriate modification be extended for use against rabbits. In some of the projects described below, the removal of rabbits and rodents were concurrent, using the same techniques (e.g. Oliveira *et al.*, 2010).

Management Strategies

The introduction of rodents to new regions as alien invasives is a major challenge to modern wildlife conservation (Veitch and Clout, 2002). At first, the complete removal of these rodents seemed impractical, and early management efforts focused on control rather than eradication. The first documented successful island rodent eradication dates back to 1951, when Norway rats were removed from Rouzic Island (3.3 ha), off the coast of France (Lorvelec and Pascal, 2005). This, and other early successful eradications, were generally unintentional by-products of normal rodent-control efforts, though serious consideration was subsequently given to removing rodents from islands intentionally. In the 1980s, more refined techniques for eradicating rodents from larger islands were developed, with a 'landmark' event occurring in 1988 when Norway rats were eradicated from New Zealand's Breaksea Island (170 ha) (Taylor and Thomas, 1993). The eradication of introduced rodents from island ecosystems has now been achieved on over 400 islands worldwide (Database of Island Invasive Species Eradications, 2013). Among documented eradication attempts, 90% have been successful, but this estimate may be inflated, as success is more likely to be reported than failure. Most of these island eradications took place in Australasia, particularly in the islands surrounding New Zealand (Howald *et al.*, 2007), and much of what we now know about the control of alien invasive rodents is derived from work done by New Zealand scientists (see, for example, Towns and Broome, 2003).

The Breaksea project, and other early programmes, relied on the deployment of rodenticide baits by hand in durable bait stations (see Fig. 18.1), usually set out in grid patterns. However, examination of the New Zealand records indicates that eradication success on larger islands coincides

Fig. 18.1. Bait stations made from lengths of corrugated plastic drainage pipe. This design has an access aperture with cover and is held in place using loops of stout galvanized wire. Bait blocks which have central holes may be wired in place to prevent rodents from removing them from the bait station. Such bait stations have been used extensively in island programmes since the 1980s.

with the development of aerial (i.e. helicopter) bait delivery, first employed in the late 1980s (Clout and Russell, 2006). Since that time, there has been a rapid growth in the size of islands on which rodent eradication has been achieved. To date, the largest island from which rodents have been eradicated is Campbell Island (11,300 ha), a subantarctic island south of New Zealand (McClelland and Tyree, 2002). This campaign, conducted in 2001 (see 'Case Studies' below), utilized aerially broadcast brodifacoum bait to remove Norway rats (Table 18.2). A programme now in progress on South Georgia in the southern Atlantic Ocean, if successful, will be larger still. Other projects to remove rodents from large islands using aerial bait applications have also taken place in North America, including Anacapa Island (296 ha) (Howald *et al.*, 2009), Rat Island (2900 ha) (Buckelew *et al.*, 2011) and Langara Island (3270 ha) (Kaiser *et al.*, 1997).

The roof rat has been eradicated from the most islands worldwide ($n = 159$), followed by the Norway rat ($n = 104$), Polynesian rat ($n = 55$) and house mouse ($n = 30$). Rats have now been removed from 14 islands with areas of more than 500 ha. However, neither roof rats nor house mice have been eradicated from an island larger than 1000 ha. House mouse eradications also have the highest failure rates, at 19% of operations, with other reported failure rates for mice as high as 38% (MacKay *et al.*, 2007), followed by Polynesian rats (10% failure), roof rats (8%) and Norway rats (5%) (Howald *et al.*, 2007).

The removal of rodents from many offshore islands has enabled significant conservation gains, but there are many situations where eradication is still not, and may never be, feasible. Where eradication is not possible, mitigation of the threat caused by rodents must be achieved by sustained control action, and this requires good knowledge of both pest and prey ecology (Innes, 2005a,b). On the New Zealand mainland, 'best practice' techniques for ongoing rodent control have been developed by the Department of Conservation (DOC). These predominately rely on the conservative method of bait application by hand using bait stations, as the risks of primary and secondary poisoning using aerially dispersed anticoagulants on mainland sites are too high (Eason *et al.*, 2002). In most situations, intervention is timed to protect vulnerable species, either during the breeding season or during rodent population explosions, and is not applied year round. A similar strategy is adopted in the long-running programmes to protect the Madeiran petrel (*Pterodroma madeira*) on the island of Madeira (Zino *et al.*, 2001) and the dark-rumped petrel (*Pterodroma phaeopygia*) in the Galapagos (Cruz and Cruz, 1996). Bait station design has advanced considerably to prevent non-target access, and bait is made 'captive' to prevent removal and caching. In New Zealand, rodent abundance is monitored using a standardized tracking index to assess the success of control programmes (Gillies and Williams, 2004).

Sustained control of rodents on the New Zealand mainland generally integrates non-anticoagulants (i.e. 1080) with first- and

Table 18.2. Successful island eradications of rodents from New Zealand islands up to 2007. (From Broome *et al.*, 2010.)

Period/Species etc.	1960–1969	1970–1979	1980–1989	1990–1999	>2000	Total
Mus musculus			1	11	3	15
Rattus exulans		1	3	23	6	33
Rattus norvegicus	2		9	19	12	42
Rattus rattus			2	8	7	17
Total	2	1	17	59	28	107
Largest size (ha)	1	1	170	1,965	11,300	–
Technique[a]	G	G,T	G,A	G,T,A	G,A	–

[a]Technique used: G, ground-applied baits; T, trapping; and A, aerially applied baits.

second-generation anticoagulant compounds (Eason *et al.*, 2010a). Current best practice dictates that bait types, toxins and lures need to be regularly changed to prevent environmental contamination (Eason *et al.*, 2002) and the development of bait shyness (Clapperton, 2006). There is increased scrutiny of the continued use of the more potent second-generation compounds, such as brodifacoum, which are only used in certain situations (Eason *et al.*, 2010a). There are also best practice guidelines for kill trapping, but this is not used without the concurrent use of poisons because traps require frequent servicing and may not achieve operational targets when rat numbers are high (King and Moller, 1997). Also, rodent species are not equally trappable, and there are further differences both among individuals and between sexes of the same species (Clapperton, 2006).

While management strategies adopted on mainland New Zealand for the removal of alien invasive rodents currently focus on poisons and traps, both pose risks to non-target species. Rodenticides, in particular, may harm the environment (see below), as they are both non-specific and toxic (Chapters 6, 16 and 17). An alternative approach is ecologically based rodent management. This combines multiple techniques, such as the reduction of refuge habitats (i.e. habitat manipulation), trap barriers, biological control and the use of rodenticides at key times. Best results are generally achieved when a combination of techniques is applied (Singleton, 1997), and the choice of techniques depends on ecological issues, agronomy, environmental awareness and sociocultural considerations. Researchers have clearly demonstrated the relationship between rodent activity and the availability of food sources in urban areas (Figgs, 2011) and highlight that simple sanitation and rodent-proofing measures could be a very cheap means of reducing rat infestation rates (Promkerd *et al.*, 2008). Within agricultural systems, researchers have demonstrated that ecologically based management can increase food production on farms where conventional management techniques are normally used (Jacob *et al.*, 2010), and can be more cost-effective than conventional control measures (Brown *et al.*, 2006). However, it remains in question whether these principles can find widespread utility in conservation, where logistical problems and the requirements for rapid effects are paramount.

Management Tools

Eradications

The removal of introduced rats and mice from ecosystems in which they are harming biodiversity is one of the most powerful conservation tools available to permit the recovery of endangered species. Although the objective of some projects is the long-term protection of areas where the complete removal of rodents is impossible, the majority are focused upon eradication. Rodents have been successfully removed from islands ranging from the high temperate latitudes to the equatorial islands and atolls of the inter-tropical convergence zone (ITCZ). These programmes have generally applied the same standardized approaches and methods primarily developed by conservation practitioners from New Zealand. Regardless of the size, location, or even the species targeted for removal, each project has followed similar principles. These continue to be applied successfully to this day, and involve applications of palatable baits containing rodenticide delivered into every potential rodent territory, so that all rodents have access to the bait. The timing of bait delivery is ideally when the target species is not breeding and is most likely to consume the bait, and when the risks to native species from either the rodenticide or disturbance from the operations themselves is minimized or can be mitigated appropriately (see Howald *et al.*, 2007).

Many eradication programmes occur on islands that are managed by governmental conservation agencies, such as National Parks and Wildlife Refuges, which seek to protect endangered and endemic species, and to restore island biodiversity. The use of rodenticides in these sensitive ecosystems presents a dilemma for ecologists because of the negative perception of pesticides held by some members of society. Proposed rodenticide use, regardless of the island, culture or socio-economics of its inhabitants, will invariably raise concerns about safety for non-targets, including humans where present, and the need for risk mitigation. Thus, the precautionary principle is often applied, and programmes are not conducted unless risks are known and either effectively mitigated or accepted. For the long-term sustainability of these projects, and to ensure the availability of the necessary tools in the future, all programmes must be compliant with the appropriate regulatory requirements. They must also have the support of communities, at the local, regional and even national levels, which recognize the project's conservation goals. The application of rodenticides during eradications is a one-time event and without subsequent release of rodenticides into the environment. Once eradication is achieved, ecosystems go through significant beneficial changes, endangered species recover and biodiversity is protected for the future.

Rodenticides

In virtually all rodent eradications, a rodenticide in a bait matrix is the primary removal tool, and this remains the only proven method in use today for large and more complex islands. Such campaigns require rodents to seek out and consume a lethal dose of rodenticide bait. However, rodent populations are well known for the inherent variability of their foraging behaviour (Chapter 1) and physiology, especially their tolerance/resistance to anticoagulants. These characteristics increase the likelihood of survivors when a selection pressure is universally applied to a rodent population, such as in a poisoning campaign. The bait, and the rodenticide used in it, must accommodate this inherent variability, which might otherwise result in eradication failure and jeopardize future attempts to remove rodents. From the perspective of an eradication programme, the ideal bait would be:

- palatable and nutritious enough to overcome competition with naturally occurring food sources;
- toxic to rodents at a single feeding;
- safe to non-target species;
- likely to remain in the treated environment in good condition for long enough to allow rodents to take a lethal dose but not to become a long-term risk to non-targets;
- readily manufactured into a pellet or block form for hand delivery into bait stations and/or broadcast (aerial or hand); and
- should not cause bait shyness or aversion.

Of course, no such ideal exists and trade-offs are made in the design of programmes to overcome any limitations. Bait used in an eradication programme must always be palatable and not elicit any bait shyness, but a compromise between how toxic the bait is to rodents and the risks to non-target species is often made.

The most commonly used rodenticides for eradications are the anticoagulants, and both the first- and second-generation compounds (Chapter 6) have been successfully used worldwide. Their advantage is a delayed onset of poisoning symptoms, which minimizes the risk of bait shyness commonly seen with the acute rodenticides. Rodents are not believed to associate the symptoms of poisoning with the toxic bait and continue to feed on bait until a lethal dose is consumed.

Rodents usually must feed on first-generation anticoagulant baits for several days to illicit a toxic effect. First-generation anticoagulants are used successfully in island eradications most frequently when bait stations are used, rather than in broadcast baiting, perhaps because of the sustained availability of bait over a long period of time in the bait stations. The major advantage of the first-generation anticoagulants over the second-generation is a lower, but not negligible, risk to non-target species through secondary poisoning.

Notwithstanding this, the second-generation anticoagulant brodifacoum, at a concentration of 20–50 ppm, is the most common rodenticide used in eradications worldwide (Howald *et al.*, 2007). Strictly from an efficacy perspective, the second-generation anticoagulants offer the highest probability of successful removal of rodents because they:

- are highly toxic to a wide range of rodent species, including all of the main alien invasives, and are often lethal at a single feeding;
- are relatively resistant to metabolism, therefore cumulative small exposures via primary (or secondary) routes will lead to a toxic effect;
- have delayed onset of symptoms after ingestion of a toxic dose – typically 24–72 h for symptoms to develop and mortality within 3–10 days; and
- can overcome any inherited resistance or tolerance observed with other rodenticides (which may be of importance on islands with historical use of rodent control).

Against their use is that the second-generation anticoagulants are also toxic to non-target species, particularly to mammals and birds (Howald *et al.*, 1999). Thus, a prerequisite for maximizing efficacy and ensuring safety is an understanding of the risks of their use and an ability to mitigate them (see below).

Bait matrix

Rodenticide baits are designed for high palatability and good nutritional content, and are shaped into forms that are compatible with the method of application and formulated to accommodate the climate in which they are to be used. For broadcast applications, the baits used are mainly compressed cereal-based pellets, each of 1–10 g, designed to be released through a hopper and of sufficient mass to penetrate forest canopies. Bait station operations typically use bait blocks, usually about 20 g each, impregnated with wax to bind the block together, and offering protection from wet and humid conditions. Both types of baits satisfy most of the target population's nutritional demands, and must be palatable to all rodents to compete with native food resources on the island. As natural food supplies are limited in many island ecosystems, rodents have evolved efficient foraging strategies to find these scarce resources. Therefore, when rodenticide baits are deployed in these situations, often at rates of many kilograms per hectare, rodents readily find and consume them.

Bait delivery

As stated previously, a fundamental requirement of rodent eradication is to deliver bait into the territories of all rodents present. Also, sufficient bait must be available for all rodents to have access to bait for long enough to overcome any social, physiological and behavioural barriers to consuming a lethal dose (Cromarty *et al.*, 2002). Bait delivery is typically achieved by one or a combination of methods. These are: bait stations spaced at regular intervals (often in a grid pattern) and filled and refilled by hand; broadcast baiting either by hand or with a bait spreader suspended beneath a helicopter; or other mechanical means (Howald *et al.*, 2007). The use of helicopters to spread bait has facilitated successful conservation efforts on much larger and more topographically complex islands with difficult terrain.

Bait stations

Bait station eradications involve the use of stations, either commercially available or locally made (Fig. 18.1), and laid out on a grid pattern. Of course, at least one station should be present in every rodent territory, although rodents will increase the size of their territory if neighbouring animals are removed during baiting. Stations are visited, checked and bait replenished on a regular basis to ensure that bait is available consistently and in adequate quantities to kill the local rodents at a rate faster than they can replace themselves through breeding (Parkes, 1993).

The density of the grid layout (i.e. distance in each direction between stations) varies depending on the ranging movements of the target species and the environment in which they live. Typically, in temperate climates, a spacing of 100 × 100 m (i.e. one station ha^{-1}) ensures enough stations to intercept all Norway rats (Thomas and Taylor, 2002). However, research has shown that roof rats may be best treated using a 50 × 50 m spacing (4 ha^{-1}) to achieve eradication over the same time period (see Thomas and Taylor, 2002). Removing house mice with bait stations may be very difficult because of their limited ranging movements, and may require stations spaced at even closer intervals (Thomas and Taylor, 2002; Oliveira *et al.*, 2010). Even working with these optimal grid densities, there are examples of failed projects (e.g. Howald *et al.*, 2004) in which bait station density may have been inadequate to intercept all rodents. Also, there may be a trade-off between bait point density and speed of control.

The use of bait stations in rodent eradications has several advantages. Bait placement is controlled and, for the most part, only the target species, and non-targets of the same or smaller size, have access to it. This serves to reduce primary exposure. Block baits may be held in bait stations on wires or rods because loose particles may be removed by rodents and left in the open; bait not consumed is easily recovered when bait boxes are used. Also, managers can monitor the progress of the eradication through observing bait uptake and its decline over time (see 'Monitoring' below). The goal is to reach a point where there is consistently no bait uptake by rodents from bait boxes, and this indicates successful eradication.

Bait station eradications also have their disadvantages. Relative to broadcast baiting, the time to eradication may be longer due to the behaviour of the target species. This is because of the time taken to overcome neophobic responses, both to bait stations and to bait (Gill and Wein, 2012), and because some individuals may dominate stations, causing bait not to be available to subordinate rodents until dominants have been killed (Thomas and Taylor, 2002). The requirement to reach all bait stations on several occasions in difficult terrain may result in high labour costs and increased safety risks to staff. Sometimes, mixed schemes are required in which bait stations are used where topography allows, with broadcast baiting elsewhere (Oliveira *et al.*, 2010). On some tropical islands, the presence of land and hermit crabs may prevent the use of ground-secured stations because of the attractiveness of the bait to these crustaceans. Crabs may congregate at bait stations and consume bait, excluding some rodents (Howald *et al.*, 2004). Bait stations may be lifted off the ground on platforms to exclude crabs, but this incurs a risk of also excluding some rodents, and hence the success of the programme. Lastly, the longer the stations are left in place, the greater the risk to non-target species, via both primary and even secondary exposure (see Howald *et al.*, 1999).

Bait station strategies

There are two strategies for rodent eradications with bait stations (Thomas and Taylor, 2002). Both involve setting out stations in a grid, but the amount of land area treated at one time will vary depending on logistical considerations.

The 'rolling front' technique involves setting out bait stations on only a portion of the area to be treated. These are checked and replenished with bait until takes decline to zero, or close to zero, indicating the removal of rodents from the treated segment. Workers then move on to bait the neighbouring segment. The stations initially baited may be left with bait to kill any survivors and to intercept any rats that may come back into the area already treated. This cycle is repeated, segment by segment, until the entire island has been treated. The advantage of the rolling front technique is that relatively few field staff are needed at any one time;. the disadvantage is that the time to eradication rodents from the island is prolonged. Additionally, spatial or temporal gaps may be present where segments meet, leading to some areas being unbaited and so putting eradication at risk.

The 'one-off' approach arms all of the bait stations simultaneously across an island. All bait stations are checked at the same schedule, ensuring that all rodents have access to bait, both spatially and temporally. The eradication progresses synchronously across the island leading to a more efficient use of resources than the rolling front technique. However, regardless of method used, the number of person days needed to service stations is similar. Of course, the number of person days needed increases with the size of the island and the number of stations used, and also with the increasing complexity of the management and servicing of a larger staff. The one-off approach seems to offer the most efficient use of resources and the probability of eradication in the shortest time possible, and is likely to be the most reliable as well.

Broadcast baiting

The application of techniques from agriculture and forestry for seeding (sowing), fertilizing and pesticide application has revolutionized rodent eradications by facilitating applications on larger and more rugged islands. Bait containing a rodenticide in small 1–2 g pellets is spread evenly across the entire infested land mass, either by gloved hand or by mechanical means, often a specialized bucket spreader suspended beneath a helicopter. If carried out efficiently, all rats have simultaneous access to the bait, thereby overcoming many of the disadvantages of the use of bait stations. Broadcast baiting does have an important disadvantage though: it involves a greater risk of the exposure of non-target species. This requires careful environmental risk assessments and implementation of risk mitigation strategies (US Fish and Wildlife Service, 2011). Broadcast baiting is also usually inappropriate for inhabited islands.

Conservation practitioners are now commonly using aerial broadcast techniques on large islands, and on those with inaccessible cliffs, thereby delivering bait into areas that are impossible to reach on foot. Broadcast application ensures bait is available to all rodents at the same time, with little intraspecific interaction because the bait is widely distributed as a food resource and indefensible by individual rodents. Thus, eradication programmes using broadcast baiting may proceed more quickly than when bait stations are used. For rodents that are actively foraging, the majority are found dead within 5–7 days (Howald *et al*., 2009).

Bait is sown (an analogy with broadcast seeding) at a fixed application rate, usually expressed as kg ha^{-1}. The bait may be either uniformly distributed across the entire land mass to be treated, or application rates may be stratified by habitat type. Application rates are not usually set to accommodate specific rodent population densities because these are rarely known. Instead, the objective is to ensure that bait is uniformly available for at least 3 or 4 days to allow enough time for rodents to overcome any behavioural constraints to consuming a lethal dose. Applications rates are adjusted to accommodate potential loss of bait to other animals present, such as native rodents, birds and (occasionally) molluscs and crustacea. The rate of degradation of bait by climatic conditions, such as rainfall, must also be considered.

Rigorous planning is essential in broadcast applications to ensure accurate deposition of bait. Straight-line transects or baiting lines are usually established, with the distance between transects dependent on the breadth of the swath along each transect, although transect disposition is entirely dependent on local topography. After bait application is complete along transects, typically from coast to coast on large islands, the next transect is treated. Applications are conducted sequentially until the entire area to be treated is covered.

Hand broadcasting involves a single applicator, or a line of applicators, spaced at regular intervals, usually 10–25 m, walking along a predefined compass bearing, or guided by GPS (global positioning system), and stopping at regular intervals (5–25 m) to spread bait. The entire line of baiters works as a single unit, keeping the line together and moving forward systematically. Alternatively, where GPS precision is high, preloaded points can guide baiters to specific locations, and allow for monitoring of where bait has been applied. The precision of application rates by hand baiting is high because the baiters are walking the island applying bait evenly across the surface area of the island. However, hand application can be very labour intensive, and safety risks to personnel need to be carefully considered in difficult terrain.

Helicopters greatly increase the speed of application and the size of islands that can be treated. Using these aircraft makes eradication feasible on islands where hand baiting is impossible due to size or difficulty of the terrain. The helicopter can fly a reliable straight line unaffected by topography and limited only by the amount of bait it can carry in the bucket, the need for reloading and refuelling and weather. Transect or swath width, which may be between 5 and 100 m, is determined by how far the bait is spread from the bucket. The application is monitored by an on-board computer, connected to a GPS, and a light bar informs the pilot, in real time, of the position of the helicopter relative to the intended transect and what adjustments in direction are required. The pilot retains control of bait application with a trigger control that opens and closes a hydraulic gate on the bucket.

While the aerial application of bait is more efficient and quicker than hand baiting, several variables influence net application rates. These are helicopter ground speed, flow rate of bait through the bucket, weather (including humidity and crosswinds), swath width, any planned overlap in swath width and surface area of the island. The higher the ground speed, the lower the net application on the ground, and vice versa. The bait flows through the bait bucket by gravity, and the rate of flow can be increased or decreased by adjustment of the orifice through which the bait discharges and the speed of the spinning paddle in the bucket; at times, it must be adjusted depending on temperature and humidity as a result of bait clogging.

Of course, some variables are not under the control of operatives, such as weather and unpredictable events that force the pilot off the track (e.g. avoidance of birds, wind gusts). Eradication plans account for some of these variables with overlapping swaths. Typically, up to 50% overlap is planned to ensure that there are no bait gaps on the ground. For example, if a target application rate of 10 kg ha^{-1} is desired, the flow rate out of the bucket and a fixed flight speed may be set to apply 5 kg ha^{-1} in a given swath. With a 50% overlap in adjacent flight swaths, the total net application rate on the ground is 10 kg ha^{-1}, which is the target application rate. Calibration of the equipment during test applications, and the influence of these factors on the bait density on the ground, are always measured before the eradication operation. Active monitoring of the application using GPS data and ground truthing confirms that the ground application rate is within the expected parameters, and if adjustments are needed, they are made either to the helicopter flight speed or the bait bucket flow rate. Finally, the topography of the island has considerable influence on the net application rate on the ground. When bait is applied by helicopter, the steeper the slope, the less bait is applied per unit area. For example, a slope of 37° results in a 20% reduction in baiting density (viz. the Pythagoras theorem).

Timing of broadcast applications

Unlike bait station eradications, where bait may be available to target rodents for many months and even years, and most non-target species can be protected from gaining access to the bait, broadcast eradications are substantially different. Bait is available to the target species for a limited period, typically measured in days, or at most a few weeks, but during that time it poses a significant risk of exposure and primary poisoning to non-target species. Therefore, the optimum strategy for broadcast eradications is to time the eradications when the rodents are most likely to eat the bait and, ideally, when the least number of individuals of non-target species are present in the treated area. In the temperate latitudes and dry tropics, the best timing is at the annual food-dependent rodent population decline, when rodents are not breeding and any migratory species present have completed breeding and moved away from the island.

In the tropics, there may be no obvious annual food-dependent population cycle, leaving no optimum window for successful rodent removal. So eradication is best timed for the least impact to non-target species. For example, on Palmyra Atoll, a broadcast application was planned for when migratory bristle-thighed curlews (*Numenius tahitiensis*), which overwinter on the atoll, were away on their breeding grounds in

Alaska. The timing of the eradication for the boreal summer minimized the risk to shorebirds. When the majority of breeding birds returned to the atoll for the winter, there was no bait available to put the birds at risk from primary exposure.

In most, if not all, cases in broadcast baiting, a second bait application is made within 14 days after the first, to ensure that bait is available to those rats that have failed to take bait at the first application. This follow-up application also accounts for any rats that may have been in the nest, and unavailable to take bait, during the first application. This phenomenon was observed recently on Palmyra Atoll, where a young rat was discovered alive weeks after the first bait broadcast, thus reinforcing the need to space the second broadcast as long as possible after the first. Typically, 10–14 days is a sufficient delay between broadcasts, but up to 3 weeks may be preferable. Unfortunately, a long delay between bait applications can be a significant logistical problem in remote locations because helicopters, equipment and personnel must stay on the island for the next application.

Monitoring

Rodent eradications are usually carried out in stages, each of which is dependent on the one before. In order to make rational decisions as the programme progresses it is necessary to monitor certain operations. Typically, monitoring is done to:

- ensure that implementation of the eradication programme is progressing as planned, and that adequate bait is delivered where it is needed, bait is consumed and target rodents are being removed, mitigation strategies are working, risks/impacts from either the rodenticide or disturbance are within the predicted range and predicted benefits to biodiversity are delivered (these are monitored in separate operations);
- comply with permits that may impose conditions on the use of rodenticides and other equipment, and on habitat disturbance; and
- contribute learning towards the development of future projects, which is particularly relevant when working in new environments and in conditions in which there have been few successful projects.

Bait application monitoring

Monitoring bait application, both spatially and temporally, is critical to meeting the first requirement of successful rodent eradication, that of delivering bait to every rodent territory. This facilitates the identification of areas where there might be inadequate bait coverage, which may result in rodents surviving the application. The use of GPS and geographical information system (GIS) software has become the standard by which bait application is monitored, regardless of how bait is delivered (Howald *et al.*, 2007). The use of this technology is fundamental to successful implementation of larger and more complex projects. GIS data, in combination with ground truthing, verifies where bait was applied and at what rate, allowing managers to make decisions about additional applications. More importantly, it tells managers what potential rodent territories did not receive bait. Because the data are geographically linked, they can be uploaded to a GPS unit and/or on-board helicopter computer/GPS to direct additional applications. GIS is an extremely valuable tool for supporting decisions on the progress of eradication projects, but the quality of data entered must be accurate, confirmed by ground truthing and with proper initial calibration, to ensure that the output is a valid representation of what is happening on the ground.

Bait station eradications greatly benefit from GIS monitoring, and this is most apparent in programmes involving large islands with many bait stations (e.g. Bell *et al.*, 2006). Each station is georeferenced and its data are uploaded into GIS systems to permit analysis at different levels of resolution, from single stations to blocks of stations and other subsets. At a minimum, the data collected are: the amount of bait put out initially and the amount consumed and added at each subsequent check. These data may be entered into small hand-held GPS-linked field computers. Data are uploaded from each unit and accumulated over time for each station. The quantities of bait removed by rodents from the stations may be used as an indicator of rodent activity over the duration of the programme. When this is reduced to zero and sustained for a predetermined period, from several months up to 2 years, eradication can be declared to have been successful.

For aerial broadcast eradications, the GPS and on-board computer are linked electronically to the helicopter and bait bucket. The GIS software, linked to the GPS, is preloaded with flight paths and overlaid on an image of the island. The computer links these flight lines to the GPS, which guides the pilot along a pre-planned route and, in combination with visual cues, prompts the pilot to begin spreading bait. The on-board computer records the position of the helicopter at the point when the bucket is opened by the pilot and bait flow begins. It then 'paints' where bait is spread, both along the flight line itself and as a visual estimate of swath width – which it provides and records. The computer also records where the bait bucket is closed and therefore where no bait has been applied. Also, where there are sensitive habitats, such as water bodies or other areas, where no bait is to be applied, the GIS data verifies the precision of the application.

Efficacy monitoring

It is to state the obvious that rodent eradications require the complete removal of a target species from a defined location, such as an island. Missing any individual, which at worst may be a pregnant female, may result in the failure of the programme. This, of course, negates all financial investment, and makes futile any non-target species impacts and short-term conservation gains obtained from the temporarily reduced rodent population. Thus, it is critically important to demonstrate that the project is successful in removing rodents and, if they are detected, to be able to respond to and implement an appropriate response to eliminate any residual individual in the treated area.

There are many different methods of measuring the effectiveness of an eradication programme, and these involve both direct and indirect monitoring tools. Live traps, kill traps and camera traps are commonly used to detect rodents (Gill and Wein, 2012). If the rodents are large and the terrain permits, direct observation may be used, sometimes with the aid of white light or infrared spotlights and other night-vision equipment. Some projects have utilized the capture and release of radio-collared individuals (Kaiser *et al.*, 1997). Indirect indicators such as tracking plates, on which rodents leave footprints indicating their presence, and flavoured chew blocks, tags, sticks and cards, on which rodents leave incisor marks, are also effective (Buckelew *et al.*, 2011). The most appropriate method depends on the nature of the island, climatic conditions and various logistical constraints, such as the frequency of access to treated areas. For example, wax census blocks may be highly effective in a cool, wet temperate environment, but they are ineffective in the desert or on tropical islands where they melt in the sun or are attractive to land crabs. Regardless of the methods used, the principles of rodent detection remain the same – several different indicators, both direct and indirect, should be used across the entire treated area, or in carefully selected representative portions of it, to maximize the probability of detecting the presence and/or absence of rodents. Such indicators, when conducted before baiting, provide an initial estimate of population density for comparison with the situation during baiting and after the programme is completed. Data obtained before baiting may be used to identify critical areas for special consideration, such as preferred habitats of rodents. These areas are used to target post-treatment monitoring to parts of the island where survivors are most likely. Of course, direct methods provide the most reliable evidence of the presence and/or absence of rodents, but these are often the most difficult to conduct.

Rodents, because of their small size, cryptic coloration and nocturnal behaviour, are often very challenging to detect, particularly in very low densities. So the final confirmation of successful eradication is usually done only after enough time has elapsed for the production of several rodent generations. This permits residual individuals to build up in sufficient number to be readily detected. In temperate ecosystems, the accepted standard is to wait 2 years, or at least two full breeding seasons. If no rodents are detected after 2 years, the eradication has very likely succeeded. In the tropics, where breeding is not seasonal, monitoring for rodents at 1 year may be sufficient time for residual rodents to reproduce in sufficient number to be readily detectable.

Monitoring data informs managers on how the bait has been applied, and the progress of the eradication, thereby ensuring that decisions are made based on accurate assessments of the situation. Should a project fail to eradicate rodents, monitoring data is essential to provide insight into what may have caused failure, and to inform planning for future projects.

Benefits of monitoring

All projects aimed at the removal of rodents for conservation have specified objectives but, once the immediate purpose of rodent eradication is achieved, the delivery of biodiversity benefits is often assumed rather than scientifically measured. Nevertheless, it is important that initial project plans should include an element in which the delivery of long-term conservation goals is directly measured. This information is an important justification for the project and provides valuable support for future funding applications. It may be sufficient to observe, over time, the recovery of a single, selected sentinel species, although broader biodiversity monitoring is obviously to be preferred. This is because the removal of rodents often has benefits that extend far beyond an increase in the numbers of a single species, or a group of species, that has been predated.

A thorough programme of benefits monitoring was conducted after the eradication of rabbits and house mice from Great Salvage Island, Portugal (Oliveira *et al.*, 2010). Protection from disturbance, nest site competition and predation of the populations of small, burrow-nesting pelagic seabirds were the main purposes of the programme, but wider biodiversity gains were also anticipated. After the successful eradications in 2002 to 2003, periodic botanical surveys revealed a dramatic recovery in the flora of the island which, in turn, supported increased populations of many invertebrate taxa. These provided an enhanced food supply for several important species of reptiles and birds, the populations of which all showed major increases. Unfortunately, the breeding success of the small pelagic seabirds could not be directly measured because their nests are inaccessible without unacceptable risk of disturbance and nest burrow collapse. However, long-term monitoring was undertaken of a larger species, Cory's shearwater (*Calonectris diomedea*), whose nests could be visited. This showed an immediate improvement in breeding success after the eradication programme (Zino *et al.*, 2008), which has continued ever since. The body size and nesting characteristics of the shearwater meant that significant benefits to this species were not anticipated, and this serves to show that broad-based biodiversity monitoring is required if we are to understand fully the benefits of rodent removal programmes.

Planning and public engagement

> Plans are nothing, planning is everything.
> Dwight D. Eisenhower

Planning is a stepwise process in projects involving rodent control for conservation. Important stages are: project selection; technical and sociopolitical feasibility assessment; design and operational planning; project implementation; and, finally, sustaining the project to secure the biodiversity of the treated area and prevent reinvasion. Details of these processes are comprehensively discussed on the web sites of the Cooperative Islands Initiative (2013) and the Pacific Invasives Initiative

(2013). The resource kits detailed there describe the planning process and, at a basic level, include:

- feasibility study – what can be done, basic considerations, and high level research needs, cost estimates, and significant challenges;
- environmental assessment – the benefits, risks, mitigations and legal compliance required to implement the project; and
- operational plan – a detailed planning document focused on delivering bait into every rodent territory, timed to maximize the probability that all rodents will be exposed to the rodenticide, that risks to non-target species are minimized and that the implementation is legal and can be completed safely by operational staff.

Cromarty *et al.* (2002) provide a good overview of the investment needed in planning and executing a rodent eradication project, focusing on meticulous and robust planning centred upon the principles of eradication and peer review. The planning must be robust enough to ensure that the project will have a high likelihood of success, will be conducted within budget, is sanctioned by appropriate authorities, can be implemented safely, that unanticipated events can be overcome and the work can be conducted with the resources available. Peer review helps to identify aspects of the project that may put the eradication at risk and provides suggestions on how to improve the plans. Organizations such as the Island Eradication Advisory Group (IEAG), managed by the New Zealand Department of Conservation, or the Island Conservation Eradication Advisory Team (ICEAT), managed by Island Conservation, are available to practitioners to engage for support, input or review of their projects.

Throughout the planning process and the implementation of the project, it is vital that all stakeholders are engaged; stakeholders are any party with an interest in the project, and may include landowners, visitors, communities, governments and the general public (Pacific Invasives Initiative, 2013). Many of these stakeholders have a vested interest in the outcome of these projects, and because of their associations with the islands, may have important knowledge and insight into local conditions that can be considered in the eradication planning process.

Long-term control

Sometimes when eradication is logistically impossible, vulnerable plant and animal communities require protection from the depredations of alien invasive rodents. In such cases, it has proved possible to initiate long-term protection plans that have met with considerable success. Such projects generally involve many of the same features and considerations as eradication but, by their very nature, require prolonged commitment of financial and other resources. In these projects, it is often possible to reduce the amount of effort required by providing protection only at specific times of the year, for example when vulnerable species are nesting. In other projects, long-term protection is provided by the placement of bait boxes which are serviced to ensure the permanent availability of poisoned bait. Such lengthy deployment of rodenticide makes necessary careful risk assessment to ensure that there are no unacceptable risks to non-target species. The long-term projects themselves are at risk to a number of influences. In particular, changes in funding commitment can jeopardize continuity and, when anticoagulants are used, the possible development of resistance must be considered.

A typical project of this kind is the protection of Zino's petrel or freira (*P. madeira*, the Madeiran petrel) on the main island (Madeira) of the Madeira archipelago. In this project, rodenticide bait has been deployed annually since 1986 for the protection of the main nest sites of the birds from predation by roof rats (see 'Case Studies' below). A similar project was conducted on the Galapagos island of Floreana to protect the closely related dark-rumped petrel (Cruz and Cruz, 1996). On mainland New Zealand, several projects have been carried out for the protection of vulnerable bird species, such as the North Island kokako (*Callaeas cinerea wilsoni*), in which areas around breeding sites have been protected from rodents by the long-term deployment of rodenticides and other control measures (Innes *et al.*, 1999).

Environmental Considerations

If logistical difficulties accompany nearly all island rodent management schemes, the potential for adverse environmental impacts is also ever present. These impacts and their assessment are addressed, in general terms, in Chapter 16. However, several features of island rodenticide applications make careful consideration of potential environmental impacts of special importance. Programmes are usually conducted in places of extreme environmental sensitivity, with the effect that any impacts that occur may be particularly visible and harmful. Also, food webs on islands tend to be relative simple, which allows rodenticides to move quickly between environmental compartments.

Those who plan and conduct programmes of rodenticide application on islands must generally consider the potential impacts on terrestrial, aquatic and marine systems. A very large quantity of information has recently become available concerning the environmental fate of the anticoagulants as a result of the recent review of these substances carried out by the European Commission, and this information is open to public scrutiny on the web site of the European Chemicals Agency (ECHA) (www.echa.europa.eu; see Chapter 6). This source of data will permit more accurate assessment of potential environmental impacts and should be considered by anyone conducting environmental risk assessments for island rodent-control schemes.

The anticoagulants, as active substances, are generally highly insoluble in aqueous media; therefore, the risks to the aquatic and marine environments presented by anticoagulants in solution are considered to be very low to negligible. Baits are usually in particulate form, but they may become available for feeding by aquatic organisms, either in suspension and/or when accumulated in sediment. The anticoagulants are generally less toxic to fish and invertebrates than they are to mammals and birds, but there may be risks to fish and other organisms if there is considerable run-off of bait particles into aquatic environments from treated areas. A recent dramatic accident, in which approximately 18 t of brodifacoum bait was deposited into the sea off the coast of New Zealand, has permitted a practical and large-scale assessment of the fate of brodifacoum in the marine environment (Primus *et al.*, 2005). The principal environmental effect observed during intensive monitoring was the appearance of brodifacoum residues in certain filter-feeding molluscs and crustacea. No vertebrate fatalities were documented among sea mammals, birds and fish that were present in the vicinity of the spill. This extreme event suggests that significant marine impacts may be unlikely as a result of the much smaller discharges into this environmental compartment that might follow baiting, even by aerial applications, during practical control programmes.

The main impacts of baiting programmes are likely to be in the terrestrial environment, via two well-known exposure routes. Non-target animals may consume baits directly (primary exposure) or they may be exposed to rodenticides when they consume, as either predators or scavengers, rodents that themselves have taken the bait (secondary exposure). Less obviously, terrestrial food webs may become contaminated when insects take cereal-based baits and are themselves taken by insectivorous animals. Such potential impacts are now well documented (Chapter 16), but even with our extensive knowledge of them, and of suitable mitigation measures, island programmes are not always free from adverse impacts (e.g. Howald *et al.*, 1999;

Buckelew *et al.*, 2011). Rodent control on the islands of New Zealand has often been carried out with thorough non-target impact assessments. The subsequent publication of these assessments provides comprehensive records of potential pathways of exposure and environmental contamination (see, for example: Ogilvie *et al.*, 1997; Dowding *et al.*, 1999; Eason *et al.*, 2002).

Such potential impacts make it essential that detailed environmental risk assessments are conducted during the planning of island rodent management schemes. These assessments should follow the standard stepwise sequence of hazard identification, exposure and effects assessment, risk characterization, risk–benefit analysis, risk reduction (where necessary) and monitoring (van Leeuwen and Hermens, 2004). A recent project using brodifacoum bait to remove rabbits and house mice from an island in the north-east Atlantic provides an example of this approach (Oliveira *et al.*, 2010). A hazard to a population of Berthelot's pipit (*Anthus berthelotii*) was identified, and further analysis indicated a risk of severe adverse impact through the consumption of bait and insects that had fed on bait. Nevertheless, the potential benefits of the scheme were considered to outweigh this risk. A variety of mitigation measures was employed, including the translocation of some individuals to a neighbouring island, taking others into captivity, covering bait points and the unproven method of deploying drinking stations containing antidote. Monitoring during bait applications revealed the predicted impact and the population was reduced by about 50%. However, monitoring after the control programme showed that the pipit population quickly recovered to its prebaiting level and, as a result of the removal of mice, which probably predated pipit eggs and chicks as well as competing for insect food, within 2 years the pipit population grew to almost four times its former density (Oliveira *et al.*, 2010).

Thorough risk assessments do not always assure favourable outcomes. An exemplary procedure of risk assessment, consultation and mitigation planning was carried out by the agencies involved before the removal of Norway rats from Rat Island in Alaska (US Fish and Wildlife Service, 2007; and see 'Case Studies' below). In spite of this, unanticipated adverse impacts were observed on non-targets, mainly because of information gaps at the planning stage and operational difficulties which prevented the application of all the mitigation measures considered necessary during planning. Once again, the affected species are expected to recover quickly and to benefit subsequently from the eradication programme. The observed impacts were determined to be within acceptable levels and to be more than offset by the potential benefits (Buckelew *et al.*, 2011), but this example serves to remind us that very large enterprises of this kind, conducted in extreme environments, are prone to influences that cannot always be predicted and controlled.

Risk–benefit analysis is often more difficult than risk assessments because the judgements made are usually subjective. Clearly, information is important on the conservation status of species thought to be at risk and on those which are intended to benefit from rodent-control schemes. Very often, by the very nature of these schemes, the species intended to benefit are extremely rare and valuable. Impacts are often predicted and, indeed, subsequently observed; but, in almost every case, beneficial outcomes are found greatly to outweigh these impacts. It should be noted that this observation does not in any way negate the need for carefully conducted and documented risk assessment procedures.

All who use rodenticides in conventional applications adopt practical measures to mitigate their adverse impacts. Similar measures are appropriate in island rodent control, but often their implementation adds significantly to the logistical difficulties. The most easily managed mitigation measures involve bait placement by hand and the use of protective bait stations (see above). These bait stations offer protection from the consumption of bait by non-target animals that are larger than the targets, protect the bait from the effects of the weather, prevent the contamination of soil and water by holding baits in place, and aid the recovery of uneaten bait at the end of treatments. Very substantial eradication schemes have recently been carried out that have successfully utilized this conservative method. Examples are the removal of Norway rats from Canna Island (1126 ha) in Scotland using almost 4400 bait stations (Bell *et al.*, 2006), and the removal of house mice and rabbits from Great Salvage Island (270 ha) using about 17,000 bait stations (Oliveira *et al.*, 2010). However, the use of hand baiting and bait stations does not, of course, prevent secondary hazard (see Howald *et al.*, 1999), although by optimizing the quantities of bait applied, this hazard is minimized.

As the size of islands intended for control programmes has increased, so operations using bait drops from helicopters have come to predominate. Mitigation is significantly more problematic in these programmes (see above). Accurate drops, in terms of area covered and the quantity of bait applied, and the careful timing of applications, are essential so that non-target species at risk are either absent from the treated area or, at least, are not breeding, so that food requirements are at a low level. Other mitigation measures, used in both hand baiting and helicopter drops, include the removal of non-targets from the treated area and the use of bait types, such as wax blocks, that are either not attractive to or not easily taken by non-target species.

It is usually possible, after non-target hazards have been identified, risks quantified and mitigation measures planned, to design control programmes in which the predicted benefits are found clearly to outweigh the potential risks. Many hundreds of such programmes have been carried out (Brooke *et al.*, 2007) and in few, if any, have adverse impacts been significant and persistent.

Ethical Considerations

By removing rodents from islands using rodenticides for the benefit of other vertebrates (and admittedly for the broader ecosystems they inhabit), we make explicit the fact that we value the lives of some animals above those of others. Our efforts to protect endangered species from rodent predation are often driven by a will to reverse the adverse impacts caused by the, albeit unknowing, negligence of our predecessors – in other words ‘we can do it, so we should do it’. There are, though, those who would argue that these sentiments are entirely misguided; that no animal’s life is worth more than that of another and that once damage is done, further human interference is unjustified and compounds our errors – their approach is ‘let nature take its course’. These discussions invoke strong feelings on both sides, nowhere better demonstrated than the legal challenges mounted to prevent recent island rat eradication programmes conducted on the western seaboard of North America (Howald *et al.*, 2009).

Ethics in rodent control generally involves discussions about animal welfare and the humaneness of control techniques. Interestingly, research in this area has illustrated striking inconsistencies between the rights of pest animals versus those of research animals (see Chapter 15; Mason and Littin, 2003). Protection levels for research animals vary between countries, but a common framework lays the foundation for many laws that apply to the use of animals in research. Many countries follow the criteria detailed in an authoritative report produced by the Nuffield Council on Bioethics, which was established in 1991 (Meerburg *et al.*, 2008). Generally, the criteria are based around the concept of the ‘three Rs’ – refinement, reduction and replacement. The Council criteria highlight that it is important to: (i) provide care for research animals, with the results obtained with a minimum of suffering; (ii) search for alternatives to using animals; (iii) provide the opportunity for research animals to lead natural lives before experimentation; and finally (iv) any animal experiments with suffering should result in the alleviation of suffering in an equal or a greater number of humans.

Although the use of animals in research can be controversial and the public has strong demands on how research animals are treated, there appears to be public apathy on the ethics of rodent-control techniques. Public attitudes to rodents most likely reflect a historical connection to filthy environments, ill health and, more recently, impacts on conservation. As a result of this, the main criterion for developing rodent-control techniques has been increased efficacy, and this has led to a situation wherein many commonly used rodent-control methods are inhumane and cause animal suffering. In particular, anticoagulants (the most widely used control technique) can cause discomfort and pain which lasts several days (Mason and Littin, 2003). Increasingly, researchers recommend that the same considerations applied to research animals should be extended to rodent pests (Chapter 15; Littin, 2010). For example, once the justification for pest control is clearly established (Littin *et al.*, 2004), control methods should not lead to intense pain or discomfort, the duration of pain should be short and escaped rodents should still be able to live natural lives (Meerburg *et al.*, 2008). Adhering to the three Rs means that both replacement (the prevention of rodent presence) and refinement (i.e. choosing control options with the highest welfare outcomes) become increasingly important, and it might be argued that these are just as important in conservation rodent control as in the more conventional kind. Reviews investigating existing control technology indicate that more humane methods do exist, namely kill trapping (with well-designed traps that are set properly and frequently monitored), electrocution and fumigation/gassing, along with rodent exclusion and the elimination of food supplies and harbourage (Mason and Littin, 2003). However, the application of these techniques in island programmes remains problematic, and new industry research must be encouraged in which humaneness and animal welfare are priorities, alongside effectiveness. Certainly, this approach is gaining traction, and New World registration requirements will facilitate the delivery of increasingly humane, species-targeted and low persistence rodenticides (Eason *et al.*, 2010b).

Aftermath

Quarantine measures, surveillance and responses to reinvasion

While there has been great success in removing rodents, they continue to invade rat-free islands (Russell *et al.*, 2008a). The establishment of rodents on islands from which they have been eradicated sets at nought all the efforts that were expended on their original removal and may be catastrophic for recovering bird, reptile, invertebrate and plant communities. Island biosecurity should consist of pre- and post-control actions, which comprise quarantine, surveillance and contingency responses. Quarantine procedures aim to maintain rat populations at low densities around sites of possible departure, both for ship-borne and swimming rodents. This includes storing cargo in rodent-proof containers, using permanent rodent-control devices on vessels and establishing rodent-proof quarantine rooms on islands (Russell *et al.*, 2007a,b). For swimming rodents, the size and nature of the water gap appear to be the greatest predictor of invasion risk. Work on Ulva Island (259 ha), New Zealand, indicates that Norway rats are detected arriving once a year from Stewart Island (1746 km^2), approximately 800 m away (Broome, 2007). Accordingly, managing islands closer than about 2 km to mainland areas will always be difficult due to higher reinvasion risk, though the presence of strong currents may reduce this ‘safe distance’.

It is important to establish surveillance procedures where reinvasion is likely. For this, there is the need to set out detection devices to discover and identify invaders, irrespective of the method of movement, before they can establish a viable population (Russell *et al.*, 2007b, 2008b). Such devices need to detect rodents at low densities, and research has demonstrated that systems involving a combination of measures give the best results (Russell and MacKay, 2005). Many of New Zealand’s offshore islands now have permanent rodent invasion surveillance systems installed on them, and these are regularly checked because dispersal of invasive rats happens rapidly (Moors *et al.*, 1992). Current best practice suggests that checking should be undertaken at least every 6 months, as invading rats can establish a large population in less than 1 year after arrival (Russell *et al.*, 2008a). To improve the ability to detect invading rodents, research has focused on improving the palatability, attractiveness and durability of rodent baits and on passive monitoring devices, such as tracking tunnels and wax chew tags, both of which record evidence of the presence of rodents (O'Connor and Eason, 2000; Russell and MacKay, 2005). The utilization of these devices, within an integrated surveillance approach, is currently seen as the most effective option, although 85% of rat incursions on New Zealand offshore islands have been detected using traps and poison bait stations (Russell *et al.*, 2008b).

Once rodents have been detected, then contingency responses to incursions should cover at least a 1 km radius around the point of incursion (Department of Conservation, 2006). Suspected evidence of rat incursion should be preserved and independently verified by experts. As speed is vital, contingency kits should be stored on islands and made immediately available. These contingency kits need to be maintained and should consist of a variety of detection and elimination devices (Russell *et al.*, 2008b). Within these kits, hand-spread, short-life, highly palatable bait is the preferred response, and traps may also be used. Finally, trained dogs have been successfully used to locate invading rats and should be employed with other methods to detect rat incursions. In conclusion, provided that island biosecurity systems are regularly maintained and tested (Russell *et al.*, 2007a), and vigilance is continual, it should be possible to keep islands rat free even where there is a high likelihood of reinvasion.

Restoration

With the ability to eradicate rodents and defend islands against reinvasion comes a new conservation goal, that of the restoration of island ecosystems. Broadly speaking, island restoration seeks to reconstruct interacting groups of native plants and animals, and usually requires the return of native species after the removal of introduced pests. In ecological terms, this is a contentious exercise, because it is usually impossible to know what existed before the rodent invasions. Until the 1980s, island management focused on the prevention of further extinctions, often through the translocation of threatened taxa. However, over the past 20 years, there has been increasing emphasis on the social and economic components that attend island management and restoration (Bellingham *et al.*, 2010). Species translocations remain an essential element of restoration for some islands, but there is now a growing realism about the dynamic nature of island ecosystems and, in particular, the role of past human activity in determining their current state. For many New Zealand islands, the role of past fire management by the Maori is now generally acknowledged as important (Atkinson, 2004), as is the crucial nutrient role that seabirds have played in island ecosystems (Towns and Atkinson, 2004). Consequently, restoration goals for islands now vary greatly from 'direct' restoration, where eradication of all non-native species is desired, to other situations, in which an attempt is made to facilitate ongoing natural processes, such as long-distance dispersal (McGlone, 2006). These latter methods are generally referred to as 'passive' restoration, and they recognize that species pools on island ecosystems are dynamic over time.

While the removal of rodents is likely to have major benefits for biodiversity, gains are often difficult to quantify. For example, there is an often a lack of baseline data from before eradication took place, together with a lack of local history for translocated native species. Additionally, most of the rodent eradications from large islands (i.e. >100 ha) have been completed since 1990, so biodiversity responses have been assessed over that short time frame (Howald *et al.*, 2007). Irrespective of this, responses on some islands have been spectacular, especially for birds. For example, on Raoul Island (New Zealand), after just 6 years without rats and with few cats, five seabird species that had become locally extinct are again breeding on the island (Thompson *et al.*, 2005). In a recent review of New Zealand island restorations, these authors conclude that a robust assessment for native biodiversity gains is only possible for 35 islands on which rodent eradication has occurred within the last 20 years. In summary, known beneficiaries of rodent eradications on these islands include two species of amphibians, 15 species of invertebrates, the northern tuatara (*Sphenodon punctatus*), seven species of geckos, 16 species of skinks, 26 species of terrestrial birds and 14 species of seabirds (Bellingham *et al.*, 2010). However, the outcomes of translocations of many of the more cryptic species remain unmeasured, and may remain so for many decades.

This lack of understanding of the ecological consequences resulting from rodent eradications has raised some concerns. For example, the benefits of eradications can vary dramatically and unpredictably, and there may even be adverse 'surprise' consequences (Courchamp *et al.*, 2003). Sometimes, the presence of a few individuals of a species that appear to be of minor importance can mask powerful interspecific interactions. For example, the removal of herbivorous aliens, such as rabbits and goats, can lead to a release of exotic plants (Kessler, 2002). There are other examples with different trophic relationships (e.g. the release of mesopredators – i.e. middle trophic-level predators – and/or competitor release; see Courchamp *et al.*, 1999; Caut *et al.*, 2007). Replicated field studies on the New Zealand mainland have also demonstrated that manipulating single species in isolation can lead to unexpected consequences for other species in the ecosystem. For example, there was the competitive release of rats following removal of the herbivorous brushtail possum (*Trichosurus vulpecula*) and the competitive release of mice following the removal of rats (Ruscoe *et al.*, 2011). Given these issues, some authors now suggest that the ongoing success of any eradication campaign is not simply the continued absence of the pest species that has been removed, but the recovery of the island ecosystem, with an absence of surprise effects (Courchamp *et al.*, 2011).

Case Studies

To end the chapter, a series of case studies is provided to exemplify practical approaches to the situations described in the preceding sections and to demonstrate the outcomes of schemes to combat rodents for the benefit of biodiversity. The schemes vary in the ways in which rodenticides were deployed, in the target species and in the campaign strategies.

Breaksea Island (1988) – an early eradication of Norway rats using bait stations

Norway rats were first confirmed on Breaksea Island (170 ha) and the adjacent Hawea Island (9 ha), New Zealand, in an ecological survey conducted in 1975. At that time, the potential of this island to provide a predator-free environment gave excellent motivation for developing rodent eradication technology. The eradication of Norway rats from Breaksea Island was a productive refinement of ground-based work tested elsewhere. Initially, rodents were targeted on Hawea Island (Taylor and Thomas, 1993), where researchers hoped that new techniques would overcome previous problems with bait station design, neophobia, poison avoidance and poison resistance. Using a system of cleared trackways, 73 plastic drainage pipes (each 100 mm wide and 400 mm long) were placed on an irregular 40 m grid 3 weeks before poisoning (Fig. 18.1). Each tunnel was loaded with two Talon Wax Block (20 g) baits (0.005% brodifacoum) that were checked and replenished daily. Eradication was achieved in 2 weeks and provided confidence for operations on the larger Breaksea Island. The Breaksea campaign was similar to that on Hawea, but stations (n = 743) were spaced more widely apart (50 m) along contour lines cut at 60 m from the coast to the summit. Large weatherproof stations containing 50 wax block baits were also positioned on inaccessible cliffs and offshore stacks. Eradication was achieved on Breaksea after 21 days of baiting and provided evidence that eradication on a large island (>150 ha) could be achieved using bait stations and a single control technique.

Madeira (1986 and ongoing) – long-term management of roof rats using permanent bait boxes

Pterodroma madeira (Freira or Zino's petrel; Fig. 18.2) had been thought extinct for decades when, in 1969, a small breeding colony was rediscovered high in the central mountain massif of the main island of the Madeira archipelago. Subsequently, damaged eggs and dead chicks with signs of rodent gnawing were found, and it was realized that breeding at the only known colony of Europe's rarest seabird was threatened by roof rats (Zino and Zino, 1986). The eradication of roof rats from Madeira was then, and still is, impossible. Therefore, in 1986, a project was mounted in which climbers using ropes deployed a cordon of 65 permanent bait boxes around the main colony to protect the petrels from predation (Zino *et al.*, 2001). The boxes each contained about 2 kg of Talon Wax Blocks (0.005% brodifacoum), which were suspended from wires within the boxes so that they did not touch the sides. Such a large quantity was required because replenishment visits were extremely infrequent. In spite of a risk of disturbing the birds, bait boxes were also deployed on the main breeding ledge. Bait takes in the years after establishment of the boxes were high, particularly from the boxes on the breeding ledge, but they then declined. However, there was no improvement of breeding success for the first 3 years of baiting; thereafter, there was a marked increase in fledging success (Zino *et al.*, 2001). Baiting has been conducted annually since 1986 and would have needed to continue indefinitely had not a devastating fire swept across the central mountain massif of Madeira on 13 August 2010, burning all the known breeding ledges just as the petrel chicks were hatching for what would have been a record breeding season. Subsequent soil erosion removed virtually all of the nesting burrows from the main ledge and most of the others. In spite of efforts by the staff of the Parque Natural da Madeira and the Portuguese Army to construct artificial burrows, little breeding has occurred on the main breeding ledge since the fire, and the recovery of *P. madeira* remains uncertain.

Fig. 18.2. An adult Zino's petrel or freira – the Madeiran petrel, *Pterodroma madeira*. This is one of the world's rarest seabirds and breeding populations of the species have been supported by rat management operations on the island of Madeira since 1986, although they were severely affected by a fire in August 2010. Photograph reproduced by permission of Dr F. Zino.

Enderby Island (1993) – eradication of mice (and rabbits) by aerial application

Mice were accidentally introduced to Auckland Island (46,000 ha), New Zealand, during the main period of sealing activity in the early 1820s. They then probably arrived on nearby Enderby Island (700 ha) in about 1850, when there was period of attempted settlement in the Port Ross area (Taylor, 1971). In addition to mice, rabbits (*Oryctolagus cuniculus*) were deliberately introduced to Enderby Island in 1865 to establish a food source for castaway mariners, and these quickly flourished. In the early 1990s, mice had only been eradicated from five New Zealand islands (of up to 217 ha) using hand baiting techniques. For the campaign on Enderby, a decision was made to use manufactured cereal-based pellets (Wanganui No. 7) containing 0.002% brodifacoum (Torr, 2002). These are palatable and toxic to both mice and rabbits. Two aerial applications of bait (18 days apart) were made using a 'Squirrel' helicopter, with an underslung bait spreader. Bait was spread at a rate of 5 kg ha^{-1}, with 10 kg ha^{-1} used in heavily rabbit-infested country. The spreader provided a 40 m wide swath of baited area, and the swathes were overlapped by 5 m to ensure complete coverage. Given that cereal bait quickly deteriorates under wet conditions, the operation was timed for summer to ensure that bait remained palatable and to target rabbits better. Several mice showing obvious signs of poisoning were found within 3 days and no signs of live mice have been observed since baiting, despite several intensive searches. Rabbits were not eradicated by the poison, but survivors where soon removed using dogs and traps, and by shooting with spotlighting. While the focus of this control effort was the eradication of rabbits, it showed that with little extra effort, other species, in this case house mice, could be targeted using aerial baiting techniques originally developed for rat eradication.

Anacapa Island (2001) – large eradication of roof rats by aerial bait application

Anacapa Island, located off California, comprises three islets, totalling 296 ha, and was infested with roof rats. The topography of the island made hand baiting impossible and the approach used, aerial sowing/seeding, was the first example of this technique employed in North America. The programme faced and overcame significant legal challenges from various groups, which tried to prevent implementation on grounds of animal welfare. The programme was also unusual because it was conducted in the presence on the island of an endemic subspecies of ground-dwelling small mammal, the Anacapa deer mouse (*Peromyscus maniculatus anacapae*), on which severe impacts were predicted. Non-target impact mitigation measures were implemented, including the removal of colonies of deer mice (comprising more than 1000 individuals) to secure laboratory accommodation and the similar removal from the islands of the majority of resident raptorial birds. The eradication was successfully conducted using specially developed 25 ppm brodifacoum bait. The reintroduction of deer mice was carried out successfully and the mouse populations quickly recovered to the densities present before the bait applications. Raptor populations also showed significant recovery after the impacts of secondary poisoning and re-release of captive birds. The conservation benefits of the removal of roof rats were quickly apparent. Hatching success among the island's population of Scripp's murrelet (*Synthliboramphus scrippsi*) showed an increase from 42 to 80%, and a second small auk species, Cassin's auklet (*Ptychoramphus aleuticus*), nested on the island for the first time since 1927 (Howald *et al.*, 2009). A population of ashy storm petrel (*Oceanodroma homochroa*) is also newly established on the island. Anticipated severe impacts on a small passerine, the rufous-crowned sparrow (*Aimophila ruficeps*), were seen and, as no specific mitigation measures were prepared for this species, its numbers remained low when they were censused in 2009.

Campbell Island (2001) – large-scale eradication of Norway rats by aerial bait application

Campbell Island (11,300 ha) is located 700 km south of New Zealand and is extremely isolated. During the 19th century, the island was primarily a base for sealing, and Norway rats established at that time (McClelland, 2011). The eradication of Norway rats was conducted in 2001. At that time, the established method for aerial application of bait against Norway rats was one bait drop of 8 kg ha^{-1} followed by another of 4 kg ha^{-1}, assuming a weather forecast of three fine nights after each drop. For Campbell Island, the cost of this was unaffordable, and the baiting rate was reduced to a single application of 6 kg ha^{-1}, with an intended 50% overlap of bait swaths guided by GPS. Given concerns regarding the low application rate, a bait acceptance pilot trial using non-toxic Pestoff 20R™ cereal pellets was conducted in 1999 using the biomarker Rhodamine. This indicated high bait uptake and the potential for 100% mortality (McClelland *et al.*, 1999). As is usual, the operation was timed for winter when natural food sources are minimal, and rodent numbers low. The bait used contained 0.002% brodifacoum. Three Bell Jet Ranger helicopters were used to spread 120 t of bait and total island coverage was quickly achieved – within 4 weeks – thanks to unexpected favourable weather. Initial monitoring using dogs, trapping and gnaw sticks was undertaken in 2003 and found no sign of rats (King, 2003). Further outcome monitoring has shown that the eradication of Norway rats was achieved. This project has proved that increasingly larger and more isolated islands can be successfully cleared of rats. Operations were facilitated by a reappraisal of accepted aerial eradication methodology and indicated that, with good planning, Norway rats can be eradicated with a single bait application on a very large remote island.

Great Salvage Island (2002) – eradication of mice (and rabbits) using a bait station grid and hand baiting

Great Salvage Island (270 ha) is situated in the north-east Atlantic and is an important breeding station for globally significant populations of Cory's shearwater (*Calonectris diomedea*), Bulwer's petrel (*Bulweria bulweria*), Barolo (previously the little) shearwater (*Puffinus assimilis baroli*), white-faced storm petrel (*Pelagodroma marina*) and the Madeiran storm petrel (*Oceanodroma castro*). Presently uninhabited, the island was once home to a small seasonal human population, and house mice and rabbits were introduced during the period of habitation (Fig. 18.3). The native vegetation had become severely degraded by rabbit grazing and impacts on the breeding seabirds by mice were suspected. A programme to eradicate both species was initiated in August 2002 by the staff of the Parque Natural da Madeira (Oliveira *et al.*, 2010). A 1 ha grid was established using GPS technology and a sub-grid of bait stations was established within this at 12.5 × 12.5 m intervals. A total of approximately 17,000 bait stations were set out and initially baited with 150–200 g of a product designed for rabbit control but which was also well accepted by mice (Pestoff 20R™, containing 0.002% brodifacoum). Precipitous cliffs were baited by hand by climbers using ropes, and very steep slopes and screes, where bait stations could not be set, were hand baited by placing bait between and under rocks. Initial bait placement took three weeks and this was immediately followed by a second round in which consumed baits were replaced. Finally, rabbit and mouse activity checks were conducted and areas of continued activity were baited a third time. Mitigation measures to protect the important breeding population of Berthelot's pipit have already been described. Eradication of rabbits was confirmed after only 3 weeks, but the removal of mice took much longer. Talon Wax Blocks (20 g containing 0.005% brodifacoum), which were more impervious to rain, were deployed at all bait stations until March 2003, when all bait was removed from the island. Monitoring for mouse activity was conducted during the subsequent years and the island was declared free of mice. Oliveira *et al.* (2010) have documented the early stages of recovery of native flora and fauna and Zino *et al.* (2008) showed a significant improvement in the breeding success of Cory's shearwater after the eradication. Similar improvement in breeding of this species has been reported as a result of roof rat control on the Chafarinas Islands in the Mediterranean (Igual *et al.*, 2005). Benefits to the smaller seabird species have not been studied but are to be expected. The removal of house mice has apparently resulted in an increase in the numbers of an endemic subspecies of lizard *Teira dugesii selvagensis*, probably because the effects of predation on eggs and young by mice have

Fig. 18.3. The landing jetty on Great Salvage Island in the north-east Atlantic. Logistics are always a major consideration in island eradication programmes. When removing house mice and rabbits from Great Salvage, all materials had to be landed at this jetty from small rigid inflatable boats (RIBs). Adverse sea conditions often made it impossible to get on and off the island.

been removed. Lizards have been seen feeding on newly hatched Cory's shearwater chicks (F. Zino, personal communication) and consumption of eggs and predation of chicks of the smaller petrel and shearwater species is a concern.

Rat Island (2008) – large-scale eradication of Norway rats by aerial bait application

The programme conducted in 2008 to remove Norway rats from the 2800 ha Rat Island (now Hawadax Island) in the Alaskan Aleutians involved the application of 46 t of 25 ppm brodifacoum bait from two helicopters. Bait applications around two freshwater lakes were conducted by hand. A thorough process of environmental risk assessment and development of mitigation strategies (US Fish and Wildlife Service, 2007) was carried out before these applications were carried out by the US Fish and Wildlife Service. Risks to several wildlife species were identified and the main mitigation measures involved the timing of the baiting, carefully defined rates of application and the use of a bait formulation that was readily biodegraded. The eradication was successful, and in 2009, the island was declared rat free. However, various logistical failures resulted in impacts to non-target species that were greater than anticipated. Only 22 bald eagles (*Haliaeetus leucocephalus*) were thought to be present on the island, but 46 were found dead (Buckelew *et al.*, 2011); 320 glaucous-winged gulls (*Larus glaucescens*) were also found dead, as were individuals of 25 other bird species. It is likely that a high proportion of the casualties found were due to brodifacoum poisoning, although only 24 (out of 34) gulls necropsied, and three other individuals of other species, were confirmed to have been killed by the rodenticide. It was thought that the eagle casualties may in part be due to these birds having fed on dead and dying gulls. Notwithstanding these substantial impacts, post-eradication monitoring conducted in 2009 has shown that the majority of bird species on the island, including glaucous-winged gulls (on which the impacts appear to have been numerically the greatest), were present in larger numbers than before the programme was carried out (Buckelew *et al.*, 2011). It remains to be seen whether bald eagles return in the same numbers as before. This is likely to be affected by the extent to which they depended on Norway rats for food. Further monitoring has been recommended to record the anticipated benefits to land birds, burrow-nesting seabirds and changes in the vegetative and intertidal communities (Buckelew *et al.*, 2011).

What Does the Future Hold for Rodent Control in Conservation?

One thing the future certainly holds is that larger land masses will be tackled to bring the benefits of rodent control for conservation to more endangered species over greater areas. A project currently in progress on the South Atlantic island of South Georgia is the largest ever attempted. The island is partitioned by glaciers, and rat-free areas are at risk as the glaciers recede to permit Norway rats to move into previously uninfested, wildlife-rich areas of the island. So there is an element of urgency in this project that is like that of few others. After a successful initial pilot project in 2011, a second area of 580 km^2 was treated in 2013 with 183 t of brodifacoum bait by helicopter drop. A third application is planned for 2015. This would result in the island becoming rat free for the first time since sealers introduced rats to the island in the 18th and 19th centuries (Long, 2003). Such massive programmes are only possible because of the steady increase in knowledge and experience that has built up over several decades.

A difficulty brought about by an ability to treat larger and larger areas is that it becomes ever more important to be able to make well-informed decisions about the most appropriate areas to treat. Fortunately, recent research has provided a template by which to estimate the conservation benefit of the removal of alien invasive animals from islands based on cost, difficulty and the conservation value of the species to be conserved (Brooke *et al.*, 2007).

A significant impediment to the removal of rodents for conservation purposes has been the potential for some of the rodenticides used, in particular the second-generation anticoagulants, to cause unwanted side effects. These are well known and predictable, and were apparent in some of the projects described as case studies in this chapter. Although, in virtually every case, cost–benefit analysis shows that the environmental benefits outweigh the observed adverse impacts, it is important that improved mitigation measures are developed and implemented. Much remains to be done to improve the techniques by which animals at risk are temporarily removed to safety while rodenticide applications take place.

The development of better mitigation strategies is important, because it is apparent that for many years to come, conservationists will remain dependent on the active rodenticide substances that are currently available in order to achieve their conservation goals in rodent pest control. Recent studies are aimed at a re-examination of rodenticides that have gone out of use and are also investigating novel compounds (Eason *et al.*, 2010a,b), but it seems unlikely that any of these will replace the use of anticoagulants in the foreseeable future.

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19 Rodent Control: Back to the Future (the Sequel)

A.P. Buckle[1] and R.H. Smith[2]
[1]*School of Biological Sciences, University of Reading, Reading, UK;*
[2]*School of Applied Sciences, University of Huddersfield, Huddersfield, UK*

Introduction: What Has Happened in the Last 20 Years?

In the first edition of this book, we used the name of a (then) popular film as the title of a concluding chapter in which we sought to summarize what had been learned about rodent control from extensive research that had been conducted and described in the book, and also to make predictions about the future direction of rodent pest management.

First and foremost, we foresaw a future in which no effective new active substances would be brought to the market to overcome the drawbacks of those already there. This was in part due to the technical complexity of such an enterprise and in part to the increasing costs imposed by growing regulatory requirements, which were considered disproportionate to the likely financial value of such a project when the product was brought to market. Our foresight in this case was depressingly accurate. No substantial changes have occurred in the 20 years since the book was published in terms of the number of effective rodenticides available to practitioners. The global market for rodenticides was then dominated by the second-generation anticoagulants and is even more so today.

In fact, rather than more, new and better rodenticides coming to the market in the intervening years, the opposite has proved to be the case. Several useful rodenticides have been withdrawn from certain markets because of the high cost of maintaining regulatory dossiers that must meet new and more stringent compliance guidelines. For example, in Europe, several important non-anticoagulant rodenticides, including bromethalin, the calciferols and zinc phosphide, have been withdrawn because of the high costs of re-registration under the requirements of the Biocidal Products Regulation. However, all of these active substances remain available for use in the USA. This begs the question as to why the regulatory dossiers presented by manufacturers in the USA are considered competent to prove that these substances are effective and safe to the US Environmental Protection Agency, while the same dossiers are inadequate to do the same job in the European Union? In a welcome development, a Task Force has been set up to bring cholecalciferol back to the European market, but this does not much alter the fact that routine rodent control with rodenticides across the European Union is reliant to an extraordinary degree on one class of chemistry – the second-generation anticoagulants (Chapter 6).

Resistance Marches On

The efficacy of the anticoagulants is being increasingly eroded by the development of resistance. In the first edition of the book, we examined the geographical extent and the severity of resistance to the anticoagulant compounds among rats and mice. We concluded that none of the resistant strains of Norway rats and house mice then known was incapable of being controlled with one of the more potent second-generation anticoagulants. This remains the case, but the advent of DNA sequencing technology has enabled us to examine the many individual genetic mutations present in more detail (Chapter 9). We now know that three of the single nucleotide polymorphisms (SNPs) commonly found in Norway rats, Tyr139Cys, Tyr139Phe and Leu120Gln, are associated with a significant degree of resistance to some of the second-generation compounds, primarily bromadiolone and difenacoum. A similar situation has arisen with the Tyr139Cys SNP in house mice. The question of whether practical resistance will develop to the most potent compounds, brodifacoum, difethialone and flocoumafen, looms large but, fortunately, there is no sign of this at the moment.

Unfortunately, the regulation of anticoagulants has taken scant regard of the growing problem of resistance. For example, in the UK, only bromadiolone and difenacoum have been permitted for use against Norway rats because the more potent compounds were restricted to use only indoors. This was because of concern within the UK regulatory authorities that these compounds presented unacceptable risks to wildlife. Foci of resistance were at first limited in area, but prolonged refusal to permit effective anticoagulants to be used against resistant rats, and the consequent almost exclusive use of two resisted active substances, bromadiolone and difenacoum, has resulted in the extensive spread of resistance SNPs in the UK, as was clearly foreseen by the late Dr John Greaves in his chapter in the first edition of this book. We now have a situation across the whole of southern England, from the Bristol Channel to the Isle of Thanet, where very few individual Norway rats exist that do not possess one of the three advanced resistance SNPs (Prescott, personal communication).

A recent review of the risk to wildlife of the five second-generation anticoagulants that was conducted in the UK has shown that their segregation into 'indoor use only' and 'use inside and outside buildings' is no longer justified. At the time of writing it appears that, belatedly, all second-generation anticoagulants may be available for rat control in the UK, provided that a regime of rigorous stewardship to promote sustainable use is implemented. This combination of a requirement to use the most potent anticoagulants to overcome resistance, and the need for stringent stewardship to minimize non-target impacts, seems to be a necessary development given the inexorable spread of resistance and growing regulatory concerns.

It seems that European regulators of biocides have learned little from the UK experience of rodenticide resistance. A recent survey of house mouse resistance in Germany has shown the presence of one or more of three mouse resistance SNPs in 24 out of 25 surveyed sites across Germany (Pelz *et al.*, 2012). Less than 10% of the animals examined during the survey were fully anticoagulant susceptible, 'wild type' individuals. In spite of this remarkable finding, regulators in Germany have recently introduced restrictions that prevent amateurs from using the effective, second-generation anticoagulants (Schwarz-Schulz, 2013). Other regulatory authorities in the Nordic countries look set to follow suit. Given the paucity of alternative rodenticides on the amateur market in Germany, it seems likely that most amateurs will be forced either to use the ineffective, first-generation compounds against domestic mouse infestations or will have to resort to trapping to keep their homes free from rodents – that really is a case of 'back to the past' rather than 'back to the future'! The effect of this on the efficacy of mouse control, and consequently on public health, and on the spread of resistance, can only be guessed.

German regulators have applied this restriction because it is assumed that amateurs will not apply risk mitigation to prevent non-target exposure (Umweltbundesamt, 2014). However, it seems unlikely that the use of small quantities of second-generation anticoagulants for the control of house mice within domestic premises poses a significant risk, especially if the use of tamper-resistant baits stations was made mandatory. The situation for house mouse control in Germany, in which one large user group can use only first-generation anticoagulants as chemical interventions, is in contrast to the regulatory situation in the UK. For several decades, no first-generation anticoagulant has been permitted for use against house mice because of the ubiquitous nature of anticoagulant resistance in this species – the very situation that we now see in Germany!

A similar regulatory position is emerging with respect to the control of anticoagulant-resistant domestic infestations of house mice in the USA. Resistance surveys of house mice conducted in the 1980s (Ashton and Jackson, 1984) demonstrated the widespread distribution of resistance and, at some locations, a high frequency of resistance alleles in resistant mouse infestations. More recently, a survey of anticoagulant resistance among house mice in the USA, using the new DNA sequencing technology (see Chapter 9), has demonstrated the presence of at least two types of genetic resistance: Tyr139Cys and Leu128Ser (Kohn, 2013). Incidentally, these mutations were also found in the survey conducted in Germany by Pelz *et al.* (2012). The survey of Kohn (2013) has shown that anticoagulant-resistant house mice carrying either the Tyr139Cys or Leu128Ser SNP, or both, were present at 41% (45 of 111) of the sites examined in the USA. At those sites, an average of about 17% of mice may possess anticoagulant-resistant genomes. In spite of the apparently widespread nature of resistance in US house mice, both at present and in the past, and the fact that the majority of rodenticides applied by domestic consumers are for the control of house mice, the US Environmental Protection Agency has implemented proceedings that will deny the use of the second-generation anticoagulants for mouse control by consumers. The reasons given for this decision are that such action seeks to prevent the exposure of children, pets and wildlife to these compounds. However, very little information appears to exist to confirm that consumer use of the second-generation anticoagulants to control domestic mouse infestations is a significant source of rodenticide non-target impacts, particularly in wildlife. Once again, a regulatory agency, with an intention to prevent non-target impacts, proposes to regulate the use of effective resistance-breaking compounds with very limited consideration of the consequences for the spread of anticoagulant resistance and public health.

Environmental Risk Assessment and Regulation

The potential for the rodenticides, particularly the second-generation anticoagulants, to have adverse environmental impacts has been long recognized. Numerous studies have demonstrated the extensive nature of wildlife exposure to anticoagulants and it is apparent that, wherever these substances are used intensively, food webs are such that a wide range of predatory and scavenging taxa may be exposed. This exposure is demonstrated by residues of the active substances found by chemical analysis of the exposed taxa, mainly in the livers (Chapter 17). These studies demonstrate unequivocally that exposure occurs and the requirement then arises to quantify the degree of risk. In Europe, environmental risk assessments rely heavily on the use of PEC/PNEC ratio (predicted environmental concentration to predicted no-effect concentration) computations (Schwarz-Schulz, 2013) to provide initial, worst-case estimates of risk (Chapter 16). A similar approach has recently been adopted in the USA in which deterministic models are used to estimate 'risk quotients' (Riley, 2011). It is not surprising that, when both the target and non-target animals are vertebrates with similar sensitivity to anticoagulant compounds, the theoretical risks calculated within these models are invariably high.

Hypothetical and predictive risk assessment models are essential when regulators have to make decisions on compounds about which they have limited practical information – such as prior to registration and in the early stages of commercialization. We should not forget, though, that the second-generation rodenticides have been used extensively and continuously for almost 40 years. In the UK, there exists a unique data set that provides information on the following: (i) quantities of these substances used; (ii) degree and nature of acute impacts; (iii) extent of background residues in numerous non-target wildlife species; and (iv) current status of wild populations of the most exposed species. The examination of these data is informative.

During the period 1989 to 2000, UK government officials conducted systematic surveys of the quantities of rodenticides applied by selected user groups (e.g. Dawson *et al.*, 2000). Analysis of these survey data show that three user groups (farmers on arable farms, farmers growing grassland for animal feed, and government local authorities) used between 1900 and 2800 t of anticoagulant baits annually in the UK. Of this, about one half was second-generation anticoagulants. These figures do not include rodenticides applied by other farming groups, such as those in animal husbandry, professional pest controllers and amateurs.

The acute impacts of these applications are monitored via the Wildlife Incident Investigation Scheme (Health and Safety Executive, 2014). In this, government officials investigate incidents involving the deaths of animals, both wildlife and pets, that are thought to have involved pesticides. During the period 1993 to 2011, these data show that acute impacts on wildlife and companion animals rarely occur in the UK when anticoagulants are applied according to recommended label-use patterns. Impacts were almost invariably caused either by accidental misuse or purposeful abuse of the products involved (Buckle, 2013). Another monitoring programme, the Predatory Bird Monitoring Scheme (Walker *et al.*, 2013), provides an annual assessment of the degree of exposure to anticoagulants of key species, which include the red kite, barn owl and kestrel. In Scotland, a similar scheme (the Scottish Raptor Monitoring Scheme) is operated that involves a wider selection of species, including buzzards (Hughes *et al.*, 2013). In both cases, the livers of birds killed by a wide range of causes, rarely anticoagulants, are examined for residues of these compounds. The analysis shows the considerable extent of anticoagulant contamination of these species (Table 19.1).

The obvious extent of wildlife contamination shown in these studies is a cause of considerable concern, and this must be set beside our inability to demonstrate, with any scientific certainty, a lack of biological effects of these (predominantly) low-level and sublethal residues (Chapter 16). However, annual surveys of UK bird populations, and periodic assessments of breeding status, conducted by the British Trust for Ornithology (BTO), offer some reassurance. UK populations of two of the bird species most exposed to anticoagulants, the red kite and buzzard, have both shown recent dramatic increases (Balmer *et al.*, 2013), with both increases occurring during a period of intensive rodenticide use. In the case of the red kite, this is due to highly successful release programmes, and in the case of the buzzard, it is due to a rapid repopulation of the natural range after the cessation of years of severe persecution (British Trust for Ornithology, 2014).

The barn owl is another case in point. BTO data show a significant increase in the UK population of these iconic birds in the period 1994 to 2010, from about 4000 breeding pairs to about 9000, with a recent 67% expansion in the UK breeding range of the species (Balmer *et al.*, 2013). This increase

Table 19.1. The frequency of residues of second-generation anticoagulant rodenticides in some species of UK birds of prey.

Species	% containing residues of one or more second-generation anticoagulant (*n*)
Barn owl (*Tyto alba*)	84 (58)[a]
Common buzzard (*Buteo buteo*)	44 (479)[b]
Kestrel (*Falco tinnunculus*)	100 (20)[a]
Red kite (*Milvus milvus*)	94 (18)[a]

[a]Walker *et al.* (2013).
[b]Hughes *et al.*, 2013).

is at least in part due to conservation measures, such as the release of captive-bred birds and the provision of artificial nest boxes on a massive scale – a reported 25,000 boxes have been put out. Unfortunately, several successive poor breeding seasons have curtailed this increase and caused recent decline. The barn owl is a warm-climate species, known to be on the northern limit of its European range in the UK (Toms, 2014). Consequently, it is subject to occasional years of breeding failure, due to cold winters with prolonged winter snow cover and wet springs; these make hunting difficult when birds are feeding chicks in the nest, and result in subsequent population fluctuations. For the time being then, widespread rodenticide contamination does not appear to be resulting in demonstrable adverse population effects in red kites, buzzards and barn owls, although this situation requires further study and great vigilance.

A fourth species that is extensively contaminated is the kestrel. PBMS surveys have recently shown that up to 100% of birds carry residues of one or more second-generation anticoagulants. Once again, populations are increasing in the south and east of the UK but appear to be declining in the extreme north and west. The reasons for this are uncertain. Studies of the food of kestrels have shown that they generally take small live prey. Specifically, kestrels are rarely found to take the rodent species – house mice and Norway rats – that are the subject of rodenticide treatments. This begs the obvious question of how, then, is such a high proportion of these birds being contaminated? The main species preyed upon in the UK by kestrels are wild small mammals, such as wood mice (*Apodemus* spp.) and voles (*Microtus agrestis* and *Myodes glareolus*). It stands to reason, therefore, that it is the contamination of these species with rodenticide that causes the consequent exposure of kestrels and, probably, to a great extent, that of barn owls, which have similar food habits.

It is likely that these wild small mammals used as prey by kestrels are exposed to anticoagulants in a number of different ways in the UK. For example, there is extensive use of these compounds in agricultural landscapes that support small mammal populations, to protect both livestock and game birds. Here, even the use of tamper-resistant bait stations permanently situated on commercial and agricultural premises by professional pest control technicians, often as a requirement of one of the audit and accreditation schemes that are increasingly common (Chapter 16), is another important route of contamination for wild non-target rodents. Wood mice and voles readily enter these permanent bait points, feed on the anticoagulant bait put into them, and are then taken as food by a wide range of predatory and scavenging animals. Only extensive contamination at the base of UK vertebrate food webs can explain the all-pervasive nature of contamination with anticoagulant rodenticides that we see today in UK wildlife. In these days of decision making based on pest and damage thresholds, and the concept of integrated pest management, it seems inconceivable that rodenticides should be so widely and permanently deployed, frequently in the complete absence of the pests they are intended to control. Alternatives to the practice of permanent baiting with second-generation anticoagulants for surveillance are urgently needed, although these must provide similar levels of biosecurity and cost-effectiveness at sites of food storage and preparation.

A Pessimistic Outlook

Rodenticides, and in particular the second-generation anticoagulants, are under extreme pressure in many regulatory jurisdictions. In our opinion, some of this pressure is justified and some is not. However, unless manufacturers and users can make a convincing case for the need for rodent pest management with chemical interventions, and develop and implement sustainable use practices, which include appropriate and proportionate mitigation measures to prevent unacceptable non-target exposure, any future edition of this book will contain descriptions of even fewer effective rodent pest management methods than this one does.

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2nd Edition

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