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Appendix 1. Currently recognised hantaviruses and the diseases they produce, the small mammal host species and host distribution. Nomenclature and distributions from Wilson and Reeder (1993).

Host subfamily	Reservoir	Virus	Disease	Distribution of reservoir
Murinae	*Apodemus agrarius*	Hantaan	HFRS	C. Europe, S to Thrace, Caucasus, and Tien Mtns; Amur River through Korea, to E. Xizang and E. Yunnan, W. Sichuan, Fujiau, Taiwan.
	A. flavicollis	Dobrava	HFRS	England, Wales; NW Spain, France, Denmark, S. Scandinavia through European Russia, Italy, Balkans, Syria, Lebanon, Israel; Netherlands
	Bandicota indica	Thai	not known	Sri Lanka, India, Nepal, Burma, S. China, Taiwan, Thailand, Laos, Vietnam; introduced to Malay Peninsula and Java
	Rattus norvegicus	Seoul	not known	Nearly worldwide
Arvicolinae	*Clethrionomys glareolus*	Puumala	not known	France and Scandinavia to Lake Baikal, S to N Spain, N Italy, Balkans, W Turkey, N Kazakhstan; Britain, SW Ireland
	C. rufocanus	not named	not known	Scandinavia through Siberia to Kamchatka, S to Ural Mtns, Altai Mtns, Mongolia, Transbaikal, N. China, Korea, N. Japan
	Lemmus sibericus	Topografov	not known	Palearctic from White Sea, W Russia, to Chukotski Peninsula, NE Siberia, Kamchatka; Nearctic from W Alaska E to Baffin Island, Hudson Bay, S in Rocky Mtns to C. British Columbia
	Microtus arvalis	Tula	not known	Spain through Europe to Black Sea and Kirov region, Russia; Orkney Islands, Guernsey, and Yeu (France)
	M. rossiaemeridionalis	Tula	not known	From Finland E to Urals, S to Caucasus, through Ukraine E to Rumania, Bulgaria, S. Yugoslavia, N Greece, NW Turkey
	M. californicus	Isla Vista	not known	SW Oregon through California, USA, to N Baja California, Mexico
	M. fortis	Khabarovsk	not known	Transbaikal and Amur Region S though Nei Mongol and E China to lower Yangtze Valley and Fujian
	M. ochrogaster	Bloodland Lake	not known	EC Alberta to S Manitoba, Canada S to N Oklahoma and Arkansas E to C Tennessee and W Virginia, USA

Appendix 1. (Cont'd) Currently recognised hantaviruses and the diseases they produce, the small mammal host species and host distribution. Nomenclature and distributions from Wilson and Reeder (1993).

Host subfamily	Reservoir	Virus	Disease	Distribution of reservoir
Arvicolinae (cont'd)	*M. pennsylvanicus*	Prospect Hill	not known	C Alaska to Labrador, Newfoundland, Prince Edwards Island; S in Rocky Mtns to New Mexico, Great Plains to N Kansas, Appalachians to N Georgia, USA
Sigmodontinae	*Akodon azarae*	Pergamino	not known	NE Argentina, S Bolivia, Paraguay, Uruguay, S Brazil
	Bolomys obscurus	Maciel	not known	S Uruguay and EC Argentina
	Calomys laucha	Laguna Negra	HPS	N Argentina and Uruguay, SE Bolivia, W Paraguay, WC Brazil
	Oligoryzomys chacoensis	Bermejo	not known	W Paraguay, SE Bolivia, WC Brazil, N Argentina
	O. flavescens	Lechiguanas	HPS	SE Brazil, Uruguay, Argentina
	O. longicaudatus	Andes	HPS	Andes of Chile and Argentina
	O. longicaudatus?	Oran	HPS	Andes of Chile and Argentina
	O. microtis	Rio Mamore	not known	C Brazil, contiguous lowlands of Peru, Bolivia, Argentina
	Oryzomys palustris	Bayou	HPS	SE USA
	Peromyscus leucopus	New York	HPS	C and E USA into S and SE Canada, S to Yucatan Peninsula, Mexico
	P. maniculatus	Sin Nombre	HPS	Alaska across N Canada, S through USA to S Baja California and NC Oaxaca, Mexico
	Reithrodontomys megalotis	ElMoro Canyon	not known	SC British Columbia and SE Alberta, Canada, W and NC USA, S to N Baja California, and interior Mexico to C Oaxaca
	R. mexicanus	Rio Segundo	not known	S Tamaulipas and WC Michoacan, Mexico S to Panama; Andes of Columbia, Ecuador
	Sigmodon alstoni	Caño Delgadito	not known	NE Colombia, N and E Venezuela, Guyana, Surinam, and N Brazil
	S. hispidus	BlackCreek Canal	HPS	SE USA, interior Mexico to C Panama, N Colombia and N Venezuela
	Unknown	Juquitiba	HPS	(Human cases from Brazil)
Non-rodent	*Suncus murinus* (insectivore)	Thotopalayam	not known	Afghanistan, Pakistan, India, Sri Lanka, Nepal, Bhutan, Burma, China, Taiwan, Japan, Indomalayan region; introduced to coastal E Africa, Madagascar, Comores, Mauritius, Reunion & coastal Arabia.

Appendix 2. Currently recognised arenaviruses and the diseases they produce, small mammal host species and host distributions. Nomenclature and distributions from Wilson and Reeder (1993).

Host subfamily	Reservoir	Virus	Disease	Distribution of reservoir
Murinae	*Arvicanthus* sp.	Ippy	Not known	S Mauritania, Senegal, Gambia, E through Sierra Leone, Ivory Coast, Ghana, Burkina Faso, Togo, Benin, Nigeria, Niger, Chad, Sudan, Egypt, to Ethiopia; S through N Zaire, Uganda, S Burundi, Kenya, S Somalia & Tanzania, to E Zambia
	Mastomys natalensis	Mopeia	Not known	S Africa as far north as Angola, S Zaire, and Tanzania
	Mastomys spp.	Lassa	Lassa fever	Africa south of the Sahara
	Mus musculus	Lymphocytic choriomeningitis	LCM	Most of world in association with humans
	Praomys sp.	Mobala	Not known	C Nigeria through Cameroon Republic and Central African Republic, S. Sudan, Zaire, N Angola, Uganda, Rwanda, Kenya, south through E Tanzania to N and E Zambia
Sigmodontinae	*Bolomys obscurus*	Oliveros	Not known	S Uruguay and EC Argentina
	Calomys callosus	Machupo	Bolivian hemorrhagic fever	N Argentina, E Bolivia, W Paraguay, WC to EC Brazil
	C. callosus	Latino	Not known	N Argentina, E Bolivia, W Paraguay, WC to EC Brazil
	C. musculinus	Junín	Argentine hemorrhagic fever	N and C Argentina, E Paraguay
	Neacomys guianae	Amaparí	Not known	Guianas, S Venezuela, N Brazil
	Neotoma albigula	Whitewater Arroyo	Not known	SE California to S Colorado to W Texas, USA, south to Michoacan & W Hidalgo, Mexico
	Oryzomys buccinatus?	Paraná	Not known	E Paraguay and NE Argentina
	O. albigularis	Pichindé	Not known	N & W Venezuela, E Panama, Andes of Colombia & Ecuador to N Peru
	Oryzomys sp.?	Flexal	Not known	Not known
	S. alstoni	Pirital	Not known	NE Colombia, N and E Venezuela, Guyana, Surinam, N Brazil

Appendix 2. (Cont'd) Currently recognised arenaviruses and the diseases they produce, small mammal host species and host distributions. Nomenclature and distributions from Wilson and Reeder (1993).

Host subfamily	Reservoir	Virus	Disease	Distribution of reservoir
Sigmodontinae	*S. hispidus*	Tamiami	Not known	SE USA, Mexico to C Panama, N Colombia and N Venezuela
	Zygodontomys brevicauda	Guanarito	Venezuelan hemorrhagic fever	S Costa Rica through Panama, Colombia, Venezuela, Guianas, to N Brazil; including Trinidad & Tobago and smaller islands adjacent Panama & Venezuela
	Unknown	Sabiá	Unnamed	(Human cases from Sao Paulo State, Brazil)
Non-rodent	*Artibeus* (bats)?	Tacaribe	Not known	(Isolates from bats on Trinidad and Tobago)

Section 2

Methods of Management

7. Rodenticides — Their Role in Rodent Pest Management in Tropical Agriculture

Alan P. Buckle

Abstract

Rodents are serious pests of tropical agriculture. Most crops are attacked, particularly those grown for food by smallholders in the tropics. Globally, principal pest species include *Sigmodon hispidus*, *Arvicanthis niloticus*, *Mastomys natalensis*, *Meriones* spp., *Bandicota* spp., *Rattus argentiventer* and *Microtus* spp. Crop protection specialists usually recommend control programs based on integrated pest management (IPM) technologies involving the use of rodenticides in combination with various techniques of habitat manipulation. However, few proper IPM schemes have been developed and implemented on a wide-scale and long-term basis. Rodenticides are much used by growers. Acute compounds, such as zinc phosphide, are popular with smallholders because they are cheap but are rarely very effective. First generation anticoagulants (e.g. warfarin) are potentially effective, but only where their use is well managed because of the need for frequent applications of bait in relatively large quantities. Baits containing the potent second generation compounds (e.g. brodifacoum and flocoumafen) are likely to be the most effective because of the small amounts of bait and labour needed when they are applied, but questions remain about their potential to have adverse environmental impacts in agro-ecosystems. Rodenticides will be important in rodent pest management in tropical agriculture for the foreseeable future but much remains to be done to optimise their use. Improved decision-making methods, the wider assessment of non-target hazard, synergies between rodenticides and other rat management technologies and more sustainable extension programs are all areas requiring development. Unfortunately, few agencies now seem willing to expend effort on such research, although novel techniques to replace rodenticides still seem a long way off.

Keywords:

Rodents, rodenticides, rodent control, anticoagulants, resistance, integrated pest management, rice, sugar cane, oil palm, tropical crops

THE RODENT PESTS OF TROPICAL AGRICULTURE

FEW TROPICAL crops are free from rodent attack. Among common crops, perhaps only mature stands of rubber (*Hevea brasiliensis*) and some crops grown for fibre, such as sisal (*Agave sisalana*), are immune from damage by these ubiquitous pests. Crops grown in tropical agro-ecosystems for food, such as cereals (rice, wheat, maize, millet, barley and sorghum), roots, fruit, legumes and vegetables are particularly susceptible to rodent depredation. Also, crops cultivated on an industrial scale in plantations, such as sugarcane, coconut, cocoa and oil palm are commonly attacked. The extent of losses in these agro-ecosystems is highly variable. Two damage models may be recognised. In the first, if left unchecked by some form of management practice, rodent populations reach the carrying capacity of the standing crop they infest. This is frequently very high due to the abundant rodent food and cover that the crops offer. Economically significant losses in the region of 5–25% are often inflicted (Wood 1994). This type of damage may be overlooked both by farmers and crop protection specialists and becomes apparent only when carefully planned damage assessment programs are implemented over large crop areas (e.g. Posamentier 1989; Salvioni 1991). Within this model, patterns of the supply of irrigation water and subsequent harvesting sometimes concentrate rodent populations from a wide area into relatively small tracts of crop land at the end of the season and some farmers then suffer very heavy losses. The second pattern of damage is one in which certain overriding climatological or demographic phenomena create specific conditions for rodent populations to reach extraordinary, or plague, levels. At such times crops may be totally devastated. The development of very high populations of *Mastomys natalensis* after unseasonal rains in East African croplands is an example of this type of episode (Mwanjabe and Leirs 1997). Another is the very high populations of rodents that occur in some parts of Southeast Asia coincident with the irregular flowering of bamboo forests (Singleton and Petch 1994).

The number of tropical rodent pest species involved is very large and appears to present a bewildering challenge to those attempting to develop sound management strategies. However, global rodent pest problems were classified following work by the Expert Consultation of the Organisation for Economic Cooperation and Development, Food and Agriculture Organization and the World Health Organisation into seven key components of global significance (Drummond 1978) and this still provides a useful framework. Six of these problems are to be found in tropical and sub-tropical, food-crop, smallholder agriculture (Table 1). The seventh is the cosmopolitan problem of rodent damage to stored products, mainly by *Rattus norvegicus* and *Rattus rattus*.

The purpose of this chapter is to review some of the learnings obtained from a number of research and development projects aimed at introducing management strategies for these pests of tropical agriculture. The majority of these projects were broadly based investigations including the assessment of damage levels, studies of rodent biology and the development and implementation of rodent management methods. In relation to the latter, many studies were based on the use of rodenticides, although a number of subsidiary techniques were frequently incorporated to provide elements of integrated pest management (IPM).

INTEGRATED PEST MANAGEMENT AND THE USE OF RODENTICIDES

Few who devise and evaluate rodent management strategies fail to advocate integrated approaches as the most reliable, long-term solutions to rodent problems (see Richards and Buckle 1987; Mwanjabe and Leirs 1997, among many others). A review of the principles of rodent IPM was recently provided by Singleton (1997). This analysis indicates that strong IPM programs must be environmentally sound, cost-effective, sustainable, capable of application over large areas and recognisably advantageous, both for growers who implement them and politicians who support and fund them. However, after many years of work by a wide range of national and international agencies very few schemes currently operate to fulfil these criteria (Leirs 1997).

All too often those who conduct rodent control programs pay only lip service to IPM ideas and rely almost solely on rodenticides. There are many reasons for this but paramount is the fact that, although potentially effective, many of the techniques that complement rodenticides in IPM are labour-intensive and their impact is not immediately obvious to those who must invest scarce resources to implement them; in effect they do not satisfy Singleton's criteria. The control of rice-field rats in Southeast Asia through habitat manipulation is a case in point.

[The following is based mainly on work with *Rattus argentiventer* (Lam 1978, 1990) but may be relevant to other rice rat species in Asia, such as *Rattus flavipectus*, *Rattus losea* and *Rattus rattus mindanensis*, and also elsewhere.] Some of the conditions of rice cultivation that exacerbate rat problems have been long understood (Buckle et al.1985; Lam 1990; Leung et al., Chapter 14).

Table 1.
The world's major rodent pests of agriculture (from Drummond 1978)*.

Rodent pest species involved	Area affected	Crops attacked
Sigmodon hispidus	Central and Latin America	rice, sugar, cotton
Arvicanthis niloticus, *Mastomys (Praomys) natalensis*	sub-Saharan Africa	food crops
Meriones spp.	North Africa, Middle East	cereals
Bandicota bengalensis	Indian sub-continent, Southeast Asia	sugar, cereals, food crops
Rattus argentiventer	Southeast Asia	rice (oil palm)
Rattus rattus, *Rattus norvegicus*, *Rattus exulans*	Oceanic islands	coconuts, food crops

* For various reasons certain regions and pests were omitted in this analysis. However, a complete list of global rodent pest problems of open-field agriculture would certainly also include those caused by *Rattus flavipectus* in southern China and Indochina, *Microtus* spp. across the Holarctic and *Mus musculus* in mainland Australia.

Rats choose to build nests for breeding almost exclusively in rice-field bunds that are more than about 300 mm wide and 150 mm above water level. They breed primarily during the reproductive stages of the rice plants and asynchronous planting allows prolonged breeding by permitting rats to move from harvested fields to others nearby where rice is still at an appropriate stage for reproduction. Weedy rice fields (Drost and Moody 1982), as well as overgrown, uncultivated areas either in or nearby rice fields provide refugia for rats and supplementary sources of food. Habitat manipulation measures to overcome these problems are obvious; a reduction in bund size, synchronous sowing/transplanting and clean rice field cultivation practices, but all are almost impossible to implement on a wide scale because of other, overriding agronomic and socioeconomic factors.

In contrast, rodenticides have a high potential to contribute useful elements within rodent IPM strategies (Singleton 1997). Of particular importance is their relatively low cost, both in terms of the price of baits in relation to the value of the crop to be protected and the labour needed to apply them. Therefore, rodenticides seem likely to remain central to rodent management strategies for some time to come.

RODENTICIDES AND THEIR USE IN TROPICAL AGRICULTURE

The types of rodenticides, the techniques used in their application and some of their advantages and disadvantages were reviewed recently in a general account by Buckle (1994). A discussion of them is given here in relation, particularly, to their application in tropical agriculture.

Acute rodenticides

The fast-acting, acute rodenticides are still much used by tropical smallholders, although zinc phosphide is now the only specific rodenticide in this class that remains widely available. In the absence of alternatives, growers frequently apply as rodenticides other compounds with high mammalian toxicities (e.g. certain organochlorine and organo-phosphide insecticides) contrary to the regulatory approval of the compounds concerned.

The benefits of the acute compounds mainly lie in their ready availability, low cost and rapid action. They are favoured by tropical farmers because their effects are apparent almost immediately after application. To be set against these advantages are their disadvantages. They are sold as concentrates and before use must be mixed with bait bases, usually cereals, to the desired concentrations. Tropical smallholders are ill-equipped to do this safely and accurately and often, cereals of sufficiently high quality to provide attractive baits are scarce. Acute rodenticides are sold as powder concentrates and are particularly prone to adulteration during manufacture and distribution. These characteristics result in baits of very dubious quality. Even when they are properly made, acute rodenticide baits have the drawback of eliciting 'bait shyness'. This is where the onset of symptoms of poisoning in sub-lethally dosed animals is so rapid that rodents are able to relate them to the novel food (the bait) which has caused them. Bait shy rodents are those that will avoid contact with the poisoned bait when it is applied in future. The likelihood of this occurring may be reduced, but not eliminated, by the use of 'pre-baiting'. In this, the bait base later to be used in the poisoning campaign is first offered without poison for several days. Rodents slowly overcome their suspicion of the novel food (neophobia) and eventually feed consistently. Only then is the acute poison introduced. The use of pre-baiting to overcome neophobia and reduce bait shyness is time-consuming, poorly understood by smallholders and rarely practised.

Probably the best results that can be anticipated with the use of zinc phosphide baits, under practical conditions, were demonstrated by Rennison (1976) on farms in the United Kingdom. Zinc phosphide baits, at 2.5% concentration, were applied by trained and experienced rodent control operators. Pre-treatment population assessment was done by census baiting and this provided a form of pre-baiting. An average level of control of 84% of *R. norvegicus* was achieved. Few good studies have been conducted on the efficacy of acute rodenticides in tropical agriculture and it is unlikely that this level of success is ever achieved. Most studies have suffered from a lack of replication, plot sizes that are too small and with insufficient separation between plots receiving different treatments, poor (or no) statistical analysis and, often, a lack of detailed explanation of the methods employed (see Chia et al. 1990 for a discussion of field trial methodology). These failings are common among field studies of rodenticides and it is not surprising, therefore, that highly variable results have been obtained (West et al. 1975; Lam 1977; Mathur 1997). In spite of the shortcomings of zinc phosphide, Adhikarya and Posamentier (1987) used manufactured zinc phosphide bait cakes in a successful large-scale rodent control campaign in cereals in Bangladesh.

The recommended concentration of zinc phosphide for field use varies from 1% to 5%. Zinc baits are generally unpalatable to rodents and a compromise between the active ingredient concentration used and the quantity of bait likely to be eaten must be reached with the objective of administering the maximum quantity of the active ingredient. The preferred concentration is probably 2–2.5% (MAFF 1976). The bait bases used are locally available cereals. They may be soaked overnight in water before the zinc phosphide is added and this is thought to enhance uptake (MAFF 1976) but reduces the stability of bait. The baits are placed in small piles of 20–50 g at intervals of 5–20 m on bunds in rice fields or, in other crops, wherever rodents are active (Lam 1977; Mwanjabe and Leirs 1997). The rate of application may be varied, both by the weight of bait used and the distance between bait points, in order to accommodate different pest infestation densities. Undoubtedly, a few days of pre-baiting with the cereal to be used later as the carrier for the active ingredient will enhance effectiveness.

First generation anticoagulants

The archetypal first generation anticoagulant rodenticide is warfarin. After its introduction in the early 1950s, a number of other compounds were developed, including pival, coumachlor, coumatetralyl, and the indandiones — diphacinone and chlorophacinone. However, with the possible exception of coumatetralyl (e.g. Greaves and Ayres 1969; Buckle et al. 1982), there is little evidence that these compounds differ much from each other in their efficacy. All these compounds are most potent when administered in small daily doses. However, their most advantageous common feature is their chronic mode of action, which means that bait shyness does not arise. These novel features required the development of a different means of quantifying the potency of the first generation anticoagulants. This was done in terms of the number of days of consumption of field strength baits required to obtain a given mortality percentile and resulted in the expression 'lethal feeding period' (LFP).

Warfarin was first developed for use against the Norway rat and it is particularly effective against that species (Table 2). Used against Norway rats in commensal situations and in animal husbandry (pig/poultry sheds, dairies, beef-rearing units) and other farm buildings (mills and granaries) the virtual elimination of Norway rat infestations was possible for the first time. However, other species are less susceptible to it and among the least susceptible are some important pests of tropical agriculture, such as *Mastomys natalensis*, *Meriones* spp., *Bandicota* spp., *R. argentiventer and R. rattus*. Greaves (1985) gave data for 'natural resistance' to warfarin for 11 rodent species, of which nine were pests of agriculture (Table 2). This shows that for only three species (*R. norvegicus*, *Sigmodon hispidus* and *Arvicanthis niloticus*) is the LFP$_{99}$ less than 14 days.

It is a reasonable conclusion that warfarin (and the other similar compounds) is unlikely to be as effective when used in agriculture as it is in commensal situations if more than two weeks of continuous no-choice feeding is required to deliver an LFP$_{99}$.

Table 2.

'Natural resistance' to warfarin of key rodent pest species as indicated by the number of days of no-choice feeding on 250 ppm warfarin baits to achieve lethal feeding period (LFP)50 and LFP99 percentiles (from Greaves 1985)

Rodent species	Feeding period (days)	
	LFP$_{50}$	LFP$_{99}$
Nesokia indica	1.9	3797.0
Acomys caharinus	5.4	239.3
Mus musculus	4.8	29.5
Mastomys natalensis	4.8	26.0
Bandicota indica	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	1.7	5.8

Even against susceptible species, the effective use of the first generation anticoagulants requires that baits are available for consumption by rodents, more or less continuously, for several weeks. Baiting programs were developed, primarily in the Philippines, for use in tropical agriculture with this requirement in mind (Hoque and Olvida 1987; Sumangil 1990). Baiting stations were put out at a density of two to five per hectare and supplied with about 150 g of bait. The bait used was generally whole or broken rice grains treated with anticoagulant powder concentrates and oil as a sticker. The bait stations were checked at frequent intervals (at least weekly) and the bait replenished. More bait and baiting stations were put out at sites where complete takes were encountered and baiting continued until takes of bait ceased or the crop was harvested. This technique came to be called 'sustained baiting' and its development, extension to smallholder groups and practical application on a nationwide basis is chronicled in the reports of the Rodent Research Centre, at Los Baños, through the mid and late 1970s. This technique remains the only practicable method of application of loose baits containing the warfarin-like compounds in tropical agriculture.

The sustained baiting technique was adapted for use with wax-block baits containing warfarin in oil palm plantations in Malaysia (Wood 1969). In this practice, a single 15 g block was placed in the weeded circles of each palm. The baits were checked at four-day intervals and replenished where they were taken. Baiting continued until the requirement to replenish baits declined to a predetermined percentage of bait placements, normally 20%. An important advantage of this system was that the use of wax blocks removed the need for fabricated bait stations to protect the bait.

All applications of rodenticides in agriculture are more cost effective, and their effectiveness more long lasting, when large crop areas are treated simultaneously. Thus, if large numbers of smallholders are mobilised to conduct baiting campaigns, the effort required by each farmer is minimised, the quantities of bait used are small and the duration of baiting is short (e.g. Buckle 1988). However, the sustained baiting method can be employed successfully by single smallholders in small plots, but almost continuous baiting may be needed. This creates a 'sink' into which are drawn rodents from a wide area. Clearly, this benefits more farmers than the one conducting baiting and may not be sustainable because its cost falls so inequitably, both in terms of effort and money. Using such a system, Sumangil (1990) used 44 kg of bait per treated hectare on small farms, during a 12-week rice growing season, where rats were numerous.

Second generation anticoagulants

Resistance to the first generation anticoagulants led to the development of a further series of compounds of greater potency that were effective against resistant rodents. These include difenacoum, bromadiolone, brodifacoum, flocoumafen and difethialone. A third generation of compounds is occasionally referred to in some publications. The last three compounds differ from the first two in being more potent but none differs sufficiently from any other to be considered in a class apart.

Early tests of brodifacoum focused on the objective of obtaining a degree of effectiveness against resistant animals that was equivalent to that of warfarin when used against fully susceptible ones. Very low concentrations in baits (5 to 20 ppm) fed over several days were sufficient to achieve this objective (Redfern et al. 1976). However, it was soon observed that 50 ppm brodifacoum baits were effective at providing very high levels of kill, against both susceptible and resistant rodents, when rodents fed for only one day on small amounts of bait (see, for example, Buckle et al. 1982, for *R. argentiventer*). However this benefit could not be readily realised as a practical advantage because the delayed effects of brodifacoum, as an anticoagulant, meant that given free access to bait, rodents consume much more before they die than actually needed to kill them. This resulted in the development of a technique called 'pulsed baiting' in which relatively small quantities of bait are put out at intervals between which there is a period in which bait is virtually absent; allowing rodents that have consumed a lethal dose to die before a subsequent application (see Buckle et al. 1984; Dubock 1984). The principle practical benefit to arise from the use of pulsed baiting in agriculture is that the quantity of bait used is substantially reduced. Successful campaigns have been conducted in which application rates as low as one to two kilograms of bait per hectare have been used (Buckle 1988). To the advantage of a reduction in the cost of bait and labour required to transport and apply it is added a reduction in the amount of active ingredient that enters the environment. The use of this technique, with wax-block baits containing one of the potent second generation anticoagulants, provides the most practical and cost-effective method of rodent control using rodenticides currently available.

Anticoagulant resistance

Resistance to anticoagulants is uncommon in tropical agriculture. There seems to be a relationship between the time taken for anticoagulant resistance to develop and the degree of selection pressure applied (i.e. the frequency of use of the anticoagulants and the proportion of the pest population exposed). In the tropics, only in oil palm plantations in Malaysia has this pressure been such that widespread resistance has developed to the first generation anticoagulants (Lam 1984; Wood and Chung 1990). In the United Kingdom, where resistance has arguably reached its current extreme, nowhere are resistant rodent populations impossible to control with available techniques, although there is a cost in terms of the need to use the more potent compounds, sometimes for periods longer than normal (Greaves 1994) and in greater quantities. This perspective is not intended to generate complacency. When anticoagulants are used in tropical agriculture it is essential to establish susceptibility baselines and to monitor pest populations for subsequent changes in susceptibility. Published guidelines set out how this should be done (EPPO 1995). These baseline studies would also provide preliminary performance data on active ingredients and the baits that contain them.

Decision-making

Rodent pest problems in tropical crops are rarely uniform, either in time or space. If a rodenticide (or any other control measure) is to be used cost-effectively, a process is required by which to decide when and where to apply it. Frequently in tropical smallholder agriculture this decision is made on the basis of subjective judgement, either by individuals or small groups of growers, and is often made too late. It is well established that cost-effective rodent management is most likely when efforts are co-ordinated over substantial crop areas. Surveillance and forecasting systems have been devised to assist decision-makers in these circumstances, based either on information on pest density or on meteorological observations.

Surveillance systems based on pest density have been worked out for sugarcane, oil palm and rice. In sugarcane, the 'Hawaii trapping index' (Hampson 1984) is widely used to determine the need for rodenticide applications. Snap-trap lines are set and rodent population density, expressed as an index of trapping success, is used as a decision-making tool. The pitfalls of this technique were pointed out by Hampson (1984) but no better method has been devised in spite of the great economic importance of the crop and the significance of rodent damage as a constraint to production in some areas.

The assessment of rodent damage can be used as another indirect index of rodent density and, if the relationship between damage and crop loss is understood, provides additional data on the latter important parameter. However, much work remains to be done in the majority of crops on the relationships between rodent population density, damage levels and crop losses. An aid to decision-making in this context is the establishment of the economic injury level, determined as follows (Dolbeer 1981):

$$T\% = 100(Y/bX) \qquad (1)$$

where

T = economic injury level;
Y = cost of control;
X = value of potential crop loss;
b = constant representing the proportion of potential loss saved by control.

Khoo (1980) proposed a systematic damage sampling scheme for use in oil palm plantations in which the percentage of palms with fresh damage to fruit bunches provided a criterion dictating the need for the application of pulsed baiting with second generation anticoagulants. Buckle (1988) conducted large-scale pilot trials of an integrated rice rat management scheme which involved farmers undertaking frequent monitoring of the percentage of rice hills with rat damage as a trigger for the need for control action. This parameter is related to, and more easily assessed than, the percentage of rat-damaged rice tillers. The advantages of these methods are that assessments may be conducted by the growers themselves, the data obtained reflects the level of rat damage/yield loss and that it is possible to target decisions so that applications may be made, when necessary, to land parcels of moderate size (e.g. 50 to 100 ha). A disadvantage is that sampling is relatively labour intensive.

Climatic factors are of limited importance as determinants of pest population densities in seasonal irrigated crops (e.g. lowland rice) and in perennial crops (e.g. oil palm) and decision-making is then best founded on measures of pest populations. However, in rain-fed crops early-warning systems based on rainfall data may be useful in predicting rodent pest outbreaks. Mwanjabe and Leirs (1997) used such a system, combined with damage assessments, to predict outbreaks of *M. natalensis* in Tanzanian maize fields. An advantage of this approach is that useful information is obtained from established national meteorological monitoring systems. Although substantial work is required on a case-by-case basis to validate the predictive accuracy of such methodology.

The mechanisms briefly described have been developed in order to target rodent control efforts more efficiently but decision-making is always likely to carry some uncertainty. Pest populations may be low until a susceptible crop stage is reached and then there may be a rapid influx from neighbouring infested habitats. This makes it necessary to monitor pest populations in quite large areas and not exclusively in croplands. All these systems require a degree of coordination from some central agency, such as a national surveillance network or a plantation crop protection advisor. Only the method developed for use in sugarcane is widely adopted and none of those designed for tropical smallholders has yet gained general acceptance. The challenge remains to crop protection researchers and vertebrate pest managers, therefore, to develop and implement practical and effective systems for monitoring rodent pest populations to allow timely and appropriate management actions to be taken in tropical smallholder agriculture. Whether direct rodent population density measures or indirect gauges, such as damage assessments, are used as the decision-making tools, a reasonable understanding of the dynamic relationships between rodent populations, damage and yield loss is needed.

ASSESSMENT OF NON-TARGET HAZARDS

In the 'good IPM check-list' provided by Singleton (1997) it is probably the need for schemes to be environmentally sound that has caused a degree of reluctance among crop protection researchers to use methods based on rodenticides in tropical agriculture. Of course, the requirement for crop protection practices to inflict no unnecessary harm on the environment is of the highest importance but refusal to work with rodenticides has now reached the level of 'chemophobia' in some quarters. In the opening chapter of this book a 20-year hiatus is mentioned during which little progress has been made in rodent pest management in developing countries. This is partly attributed to too much an emphasis on rodenticides. However, the contention that very little innovative work on rodenticides has been done in tropical agriculture for the past 10 years is borne out by a study of the reference list of this chapter and very few projects receiving funding from international agencies have included any substantial element concerned with improving rodenticide applications.

Methods for the assessment of the potential for rodenticide applications to harm the environment are well established (Edwards et al. 1988; Brown 1994). Generally, rodenticide applications pose negligible risks to soil and aquatic systems because of the nature of the compounds and their methods of use. This is particularly the case with anticoagulants. Baits are discrete, used at low rates of application, and carry low concentrations of, usually, insoluble active ingredients, which are bound readily to soil particles and do not move into plants. However, by their nature, all rodenticides are potent vertebrate toxicants. Their principle risks lie in the potential for non-target animals to consume directly baits laid for rodents (primary poisoning) and for scavengers and predators themselves to be poisoned when consuming the bodies of contaminated rodents (secondary poisoning). Those few extensive field studies that have been performed to quantify these potential effects (Tongtavee et al. 1987; Hoque and Olvida 1988) have shown that pulsed baiting with wax blocks containing second generation anticoagulants poses few risks to wildlife populations in Southeast Asian rice fields, but more studies are needed both in rice and in other agro-ecosystems.

All rodent management techniques have the potential to affect the environment adversely and this is not restricted only to those methods based on rodenticides. For example, the habitat modification methods often recommended in rice fields (removal of weedy land patches, lowering of bunds, increasing field size, periodic deep flooding of growing areas and extensive synchronous planting) would have a significant detrimental effect on a very wide range of non-target taxa that rely on these remnant habitats as their only footholds in an otherwise ecologically barren rice monoculture. Such potential impact needs to be weighed against the possible effect of occasional rodenticide use on a limited number of predatory and scavenging species, but such thinking is seldom done.

EXTENSION

The fact that smallholders are the most likely agency by which rodent control measures, particularly rodenticides, are to be applied is often overlooked by those developing management techniques (Posamentier 1997). Conflicting pressures on smallholders' time and money, their uncertain perception of the importance of the pest problem being addressed and many other socioeconomic factors jeopardise the sustainability of otherwise well-designed and cost-effective schemes. Adhikarya and Posamentier (1987) undertook a 'knowledge, attitude and practice' (KAP) survey to establish first base-line information on rodent control practice and perceptions among smallholder cereal growers in Bangladesh. Armed with this information they designed a multi-media campaign to modify beliefs and stimulate action. This substantial program met with considerable initial success but its long-term impact is uncertain.

It is tempting to look for successful models of extension of sustainable rodent control programs and attempt to draw lessons from them. A search for such models in current smallholder tropical agriculture is largely fruitless (Leirs 1997). However, oil palm plantations in Malaysia have long benefited from well organised control programs based on anticoagulant baiting. These programs are founded on a base of long-term research on the biology and control of the pest funded by those with most to gain from its results, the plantation sector agri-businesses. As a result, *Rattus tiomanicus* is arguably the best understood rodent pest of tropical agriculture (see Wood 1984; Wood and Liau 1984 a,b). Within an estate, or estate group, rat management decisions are made by a single person or small team, on the basis of well-understood economic criteria. Resources are usually available to conduct control operations as and when necessary. Rodenticide applications are made by trained workers, with no other distracting tasks on the day of application, and baits are applied over extensive areas with reasonable expectation, therefore, that the investment will be rewarded. The situation in smallholder cropping could not be more different. Several agencies may be responsible for decisions, including government crop protection, surveillance and extension services, farmer groups and individual growers; all with their own inertia and affected by different motivational factors. The financial implications of action or inaction are poorly understood and money is rarely available when it is needed. Work is done by poorly-trained smallholders, with conflicting time constraints, and the treatments are too often made on small areas with little chance of return on investment from higher crop yields. In some respects this is an unequal comparison however. Oil palm is a perennial crop and lends itself to rodent pest management because of the constancy of conditions within crop fields. Whereas, smallholder systems based on a mosaic of crop types and pest problems present much more difficult conditions. Nevertheless, until some of the problems mentioned above are overcome the current poor status of rodent pest management in tropical agriculture mentioned by Leirs (1997) and in the first chapter of this book will remain.

CONCLUSIONS

In the medium and long-term we look forward to the introduction of novel technologies for rodent pest management The beginnings of some of these are described elsewhere in this book. Those engaged in their development must keep sight of the reasons for the past failure of what were considered to be well-designed crop protection systems but which proved to be impractical or unsustainable (Singleton 1997). Presently, however, there is an urgent need for improved rodent pest management in many smallholder agro-ecosystems in order to alleviate immediate hardship. For the time being these are best founded on IPM principles, with rodenticides used as an important element. However, more work is still needed. Decision-making systems are required to help hard-pressed crop protections workers to determine when and where management programs are needed. More extensive field studies of the non-target hazards of rodenticides are required so that objective data are available in order to dispel fears, if these prove to be unwarranted, of unacceptable adverse environmental impacts. Also, the development is needed of innovative extension technologies to motivate smallholder farming communities and to make well-designed rodent pest management programs sustainable.