

*Chapter 1*

## **SUSTAINED AGRICULTURE: THE NEED TO MANAGE RODENT DAMAGE**

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### *Introduction*

The need for sustained agricultural production increases as the world's human population increases, many natural resources grow scarce, and the amount of land devoted to agriculture declines. For example, Vietnam loses 30,000 ha annually of prime rice land to urban development, yet it is the second highest exporter of rice in a world market that reached crisis levels during 2008 (Meerburg et al., 2009b). Between 1960 and 2000, the world's population doubled; in Asia alone the annual population growth until 2020 is estimated at 75 million, which is a lot of new mouths to feed (FAO, 2008). Hence, feeding the world's growing population continues to be a challenge for governments, especially in light of accelerated population growth, loss of agricultural land to urbanization and industrialization, shortage of agricultural labor due to migration of youth to cities, sustained economic growth leading to increase demands for meat protein (energy to produce 1 kg of meat protein requires 5 times that of proteins from cereals (Kawashima et al., 1997)), and pressures brought by climate change, loss of biodiversity, growing water scarcity, liberalized trade regimes, and inappropriate technology applications (e.g. growing of some food crops for bio-fuels). The future requires a sustainable agriculture base in which farms can produce food without causing severe or irreversible damage to ecosystem health.

Agro-ecosystems are complex systems that have transitioned from natural ecosystems by progressively incorporating interactions of three distinct systems: the ecological, the social/economic and the agricultural (Kogan and Lattin, 1999). Agro-ecosystems around the

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world range from modern, capital-intensive, large-scale monocultures to traditional, small, fragmented fields (e.g. in the Red River delta of northern Vietnam the average family holding is less than 0.25 ha, usually divided into 2 or 3 plots), and free-range livestock operations to confined livestock operations. Many other organisms compete with humans for food and natural resources, including wild animals, weeds, insects, and plant and animal pathogens. Although a wide array of vertebrate species cause damage in agriculture (Conover, 1998; Olsen, 1998; Putman, 1989; Wywiałowski, 1998), rodents pose one of the most serious threats to food production worldwide (Leirs, 2003; Meerburg et al., 2009b; Singleton et al., 2003; Stenseth et al., 2003). In this chapter, we review the rodent species involved, the types and levels of damage caused, the potential management options to reduce damage by rodents, and some research needs. Rodents also are carriers of >60 diseases that affect humans, some which can cause significant debilitation and can lead to affected smallholder farmers falling into an even greater poverty pit. We will not review rodent zoonoses but instead refer you to a recent review (Meerburg et al., 2009a).

## THE NATURE OF RODENTS

Approximately 42% of all mammalian species in the world are rodents; this amounts to about 2,277 species of rodents (Wilson and Reeder, 2005). They occur on all continents with the possible exception of Antarctica. However, even there, commensal rodents may have been accidentally introduced to the inhabited research stations. Rodent species have adapted to all life-styles: terrestrial, aquatic, arboreal, and fossorial (underground). Most rodent species are small, secretive, nocturnal, adaptable, and have keen senses of touch, taste, and smell. For most species of rodents, the incisors continually grow throughout their lifespan, requiring constant gnawing to keep the incisors sharp and at an appropriate length. In contrast to the normally small-sized body rodent, the capybara of South America can reach 70 kg in mass. Needless to say, a rodent this size can cause much damage to crops and rangeland (Ferraz et al., 2003; 2007). Alderton (1996) has written a fascinating account of the world of rodents and the love-hate relationship that has always existed and presumably always will between rodents and humans.

Rodents have ecological, scientific, social, and economic values (Dickman, 1999; Witmer et al., 1995). Rodents are important in seed and spore dispersal, pollination, seed predation, energy and nutrient cycling, the modification of plant succession and species composition, and as a food source for many predators. Additionally, some species provide food and fur for human uses, and can provide an ecosystem service for smallholder farmers through consuming pests of their crops (e.g. *vev*ivores that feed on invertebrate pests in rice agro-ecosystems (Stuart et al., 2007)). Hence, the indiscriminate removal of rodents from ecosystems, including agro-ecosystems, is not the best management option in many cases (Aplin and Singleton, 2003; Brakes and Smith, 2005; Villa Cornejo et al., 1998).

Rodents are known for their high reproductive potential; however, there is much variability between species as to the age at first reproduction, size of litters, and the number of litters per year. In the tropics and sub-tropics, reproduction can continue throughout the year, whereas, in more northerly latitudes, reproduction is usually seasonal and limited. Under favorable conditions, populations of some species such as the *Microtines* can irrupt, going

from less than 10 per ha to a thousand per ha in the period of a few months (Korpimäki et al., 2004). During these periods of irruption, rodents will often invade crop fields and cause severe damage. From a management perspective, most rodent populations will exhibit a compensatory response to a severe population reduction with earlier age to sexual maturity, higher pregnancy rates, larger litter sizes, more litters per year, and a higher survival rate of young. Currently, there are no commercial products available to reduce the fertility of rodents although research in this area is on-going (discussed later in chapter).

As part of their life strategies, individuals of most rodent species have short life-spans and the annual mortality rate in a population is high, often about 70% (O'Brien, 1994; Singleton, 1989). Although rodents, generally, have good dispersal capabilities, unless conditions are very favorable, mortality rates during dispersal are quite high. Rodents succumb to starvation, predation, disease, drowning and other accidents, and various other mortality factors. Hence, most rodent species exhibit a classic r-selected life strategy: high reproductive rate with high mortality rate. An important management consideration is any quick reduction of a rodent population using lethal means (often with rodenticides as discussed later), will often result in a quick rebound of the population if no other actions are taken.

There are many interesting dynamics to various rodent populations that should be understood to better facilitate their management and to reduce damage (Batzli, 1992; Macdonald et al., 1999). Some populations go through annual cycles that may include high and low densities, active and inactive periods, reproductive and non-reproductive periods, and dispersal periods. To avoid inclement periods, some species exhibit winter dormancy (hibernation), while some species have summer dormancy (estivation) during hot, dry periods. Some species exhibit multi-year cycles; for example, the Microtines often reach population peaks (irruptions) every 3-5 years. While these cycles have been studied for decades, the driving factor(s) has not been definitively identified, but may involve long-term weather patterns, long-term nutrient cycles, predation, disease, and intra-specific social interactions (Krebs, 1996). During the early development of principles of population ecology, Charles Elton (1942), plus notable North American contemporaries such as Davis, Emlem and Howard (see Davis, 1987; Howard, 1988a), emphasized the importance of understanding the population biology of particular rodent species for effective management; one must take into consideration the specific demographics and capabilities of the species, along with the vagaries of cycles and periods of inactivity (e.g., Marsh, 1994) and the social and ecological context of modified agricultural landscapes (Singleton et al., 1999). Some recent reviews of the biology and ecology of pest rodents in the U.S. and control efforts include: pocket gophers (Marsh, 1992; Witmer and Engeman, 2007), ground squirrels (Marsh, 1994), voles (Witmer et al., 2009), and house mice (Witmer and Jojola, 2006).

## RODENT DAMAGE AND THE SPECIES CAUSING DAMAGE

One of the serious threats to adequate world food production is the large volume of food production being consumed or contaminated by rodents. Some 280 million malnourished people could benefit if pre- and post-harvest losses by rodents are reduced (Meerburg et al.,

2009b). Fortunately, on a global-scale, only about 5-10% of the 2,277 species of rodents are serious agricultural pests (Witmer et al., 1995; Stenseth et al., 2003; Singleton et al., 2007a).

**Table 1. Examples of rodents causing agricultural damage in various parts of the world.**

Continent/Region	Genera	Crops Damaged	References
North America	<i>Cynomys</i> , <i>Geomys</i> , <i>Marmota</i> , <i>Microtus</i> , <i>Spermophilus</i> , <i>Thomomys</i>	Grains, alfalfa, flax, cotton, potato, sugar cane, trees	Marsh, 1984; 1988
Central & South America	<i>Ctenomys</i> , <i>Holochilus</i> , <i>Octodon</i> , <i>Oryzomys</i> , <i>Sigmodon</i> , <i>Zygodontomys</i>	Grains, beans, cotton, sugar cane, potato, cassava, bananas, trees	Elias and Fall, 1988; Hilje and Monge, 1988; Jackson, 1988
Europe	<i>Apodemus</i> , <i>Arvicola</i> , <i>Clethrionomys</i> , <i>Critetus</i> , <i>Microtus</i> , <i>Pitymys</i>	Grains, alfalfa, potato, beets, trees	Lund, 1984; 1988
Africa	<i>Arvicantis</i> , <i>Mastomys</i> , <i>Meriones</i> , <i>Rhabdomys</i> , <i>Tatera</i> , <i>Thryonomys</i> , <i>Xerus</i>	Grains, cotton, sugar cane, potato, cassava, groundnut, plantation crops, trees	Fiedler, 1988; Smythe, 1986; Taylor, 1984
Middle East	<i>Hystrix</i> , <i>Meriones</i> , <i>Microtus</i> , <i>Nesokia</i> , <i>Psammomys</i> , <i>Spalax</i>	Grains, peanuts, root crops, vegetables, dates, trees	Moran and Keidar, 1993
South Asia	<i>Arvicola</i> , <i>Bandicota</i> , <i>Spermophilus</i> , <i>Cricetulus</i> , <i>Meriones</i> , <i>Microtus</i> , <i>Nesokia</i> , <i>Rattus</i> , <i>Tatera</i>	Grains, cotton, potato, sugar cane, vegetables, groundnut, banana, mango, pineapple, trees	Prakash, 1984; Prakash and Mathur, 1988; Zhi and Cheng- Xin, 1984
Southeast Asia/Pacific Islands	<i>Bandicota</i> , <i>Callosciurus</i> , <i>Mus</i> , <i>Rattus</i>	Grains, root crops, cocoa, sugar cane, oil palm, coconut, pineapple	Benigno and Sanchez, 1984 ; Hoque et al., 1988
Australia	<i>Rattus</i> , <i>Mus</i> , <i>Melomys</i>	Grains, sugar cane, macadamia nuts, banana, avocado, citrus	Caughley et al., 1998; Stenseth et al., 2003

On any given continent, there are generally about a half-dozen to a dozen genera that cause significant damage (Table 1). This list primarily includes native species of rodents, except for Australasia and some Asian countries. These species mainly cause damage to crops in the field. Additionally, there are several species of commensal rodents that cause damage mainly to physical structures (e.g., electrical wiring; fibre optics) and to food stuffs in storage by feeding and by contamination of stored food stuffs with their urine and feces (Ahmad et al., 1990; Proctor, 1994). The commensal rodents include the Norway rat (*Rattus norvegicus*), the ship or black rat (*R. rattus*), the Polynesian rat or kiore (*R. exulans*), and the house mouse (*Mus musculus* and *M. domesticus*). These species live in close proximity to humans, exploiting the favorable conditions that are created for them. As a result, they have spread throughout most of the world and cause significant losses of stored food stuffs. These rodents, along with some native rodent species, also pose health threats because of the many diseases they can carry that are transmissible to humans and livestock (Gratz, 1988; Meerburg et al., 2009a). Under some climatic conditions, commensal rodent populations will erupt, invade

**Table 2. Levels of rodent damage to various crops around the world.**

Region	Crop	Rodent	Damage Level	Reference(s)	
North America	Wheat, alfalfa	Ground squirrel	25%	Askham, 1994	
	Alfalfa	Vole	4%	O'Brien, 1994	
	Peas	Vole	3-9%	Witmer et al., 2007c	
	Corn	Rodents	1-100%	Hygnstrom et al., 1996	
	Orchard fruit	Vole	35-66%	O'Brien, 1994	
	Orchard fruit	Vole	36%	Askham, 1988	
	Orchard trees	Vole	30%	Sullivan et al., 1987	
	Rangeland forage	Kangaroo rat	11%	Hawthorne, 1994	
	Rangeland forage	Prairie dog	18-90%	Hygnstrom and Virchow, 1994	
	Rangeland forage	Pocket gopher	25%	Case and Jasch, 1994	
	Stored grain contamination	House mice	76%	Timm, 1994a	
	Stored grain	Norway rat	18%	Timm, 1994b	
	Power outages	Tree squirrel	24%	Jackson, 1994	
Central/South America	Beans	Rodents	5-10%	Meehan, 1984	
	Corn		26%	Ferraz et al., 2003	
	Sugarcane	Pocket gopher	21%	Villa-Cornejo, 2000	
	Coconut	Rodents	77%	Elias and Fall, 1988	
	Alfalfa	Rodents	10-30%	Elias and Fall, 1988	
Europe	Sugarbeets	Wood mice	2-26%	Pelz, 1987	
	Alfalfa	Vole	2-46%	Truskowski, 1982	
	Orchard trees	Vole	25%	Lund, 1988	
	Horticulture	Voies	5-10%	Lund, 1988	
	Stored grain contamination	Rodents	>90%	Meehan, 1984	
	Farm fires	Rodents	50%	Richards, 1989	
Africa	Corn	Rodents	20-30%	Ojwang and Oguge, 2003	
	Corn	Rodents	26%	Bekele et al., 2003	
	Sorghum	Multimammate rat	30%	Fiedler, 1988	
	Rice	Rodents	80-100%	Fiedler, 1988	
	Corn, sorghum, rice, legumes	Multimammate rat	48%	Mwanjabe et al., 2002	
	Cacao	Rodents	4-12%	Fiedler, 1988	
	Oil palm	Cane rat	23%	Fiedler, 1988	
	Stored rice	Rodents	2-5%	Fiedler, 1988	
	Rice	Rodents	7-30%	Prakash and Mathur, 1988	
	Rice	Rodents	5-15%	Rao, 2003	
	Wheat	Rodents	12-60%	Prakash and Mathur, 1988	
	Sugarcane	Rodents	11%	Prakash and Mathur, 1988	
	Corn	Rodents	1-14%	Prakash and Mathur, 1988	
	Grains	Vole	50%	Wolf, 1977	
	Groundnut	Rodents	4-26%	Prakash and Mathur, 1988	
	Alfalfa	Vole	16-25%	Wolf, 1977	
	Rangeland forage	Vole	80%	Nolte, 1996	
	Southeast Asia & Pacific Islands	Rice	Rodents	5-30%	Singleton, 2003
		Rice (Indonesia)	Rodents	16%	Singleton et al., 2005
Rice		Rodents	5-27%	Hoque et al., 1988	
Corn		Rodents	5%	Hoque et al., 1988	
Sugarcane		Rodents	2-10%	Hoque et al., 1988	
Coconut		Rodents	12-65%	Hoque et al., 1988	
Pinapple		Rodents	10%	Hoque et al., 1988	
Cacao		Rodents	50-60%	Hoque et al., 1988	
Macadamia nut		Rodents	5-10%	Tobin, 1992	
Australia	Macadamia nut	Rodents	30%	Caughley et al., 1998	
	Sugarcane	Rodents	14-57%	Caughley et al., 1998	
	Grains, sunflower	Rodents	12-25%	Brown et al., 2004	

crop fields and pasture lands and cause significant damage. This has happens regularly with house mice in Australia (Brown et al., 2004; Caughley et al., 1998). There have been occasional irruptions of house mice in Hawaii (Tomich, 1986) and California (Pearson, 1963). There are irruptions of populations of rats and other native rodent species in India and Bangladesh (Chauhan, 2003), Laos (Khamphoukeo et al., 2003) and South America (Jaksic and Lima, 2003) associated with the flowering of bamboo. The episodic outbreaks in eastern India, Bangladesh and western Myanmar appear to be linked to a clonal species of bamboo that only blooms and sets fruit every 50+ years (Chauhan, 2003) and these outbreaks lead to significant food security issues (Belmain et al., 2008). Additionally, the commensal rodents have become established on many islands where they cause significant damage to natural resources and can lead to native species of animals, birds, and plants becoming endangered or extinct (Angel et al., 2009; Murphy et al., 1998; Witmer et al., 2007a; Witmer et al., 2007b).

The types of agricultural damage inflicted by rodents include the direct feeding on seeds and plants at all stages of the cropping cycle (e.i., planting, vegetative growth, maturation, and pre- and post-harvest). Additionally, rodents cause damage from their burrowing activities which can result in levee failures, flooding of fields, loss of water resources, and the undermining of structures and foundations (Joshi et al., 2000; Stuart et al., 2008). Burrows and burrow openings can result in damage to farm equipment and injury to workers or livestock. Through their gnawing activity, rodents can damage equipment, irrigation tubing, and buildings. For example, house mice cause significant damage to insulation in confined livestock operations (Hygnstrom, 1996). Chewing through wiring can result in power failure or devastating fires (Caughley et al., 1994). Rodents also compete with livestock for feed whether in confined operations or open rangeland. They also contaminate stored food with their feces and urine. Witmer and Engeman (2007) reviewed the many types of damage that can be caused by a single group of rodents, the fossorial pocket gophers.

## **LEVELS OF RODENT DAMAGE**

In most agricultural settings, there is some level of rodent damage. Sometimes, the amount of damage may be small and considered inconsequential costs of business. Indeed, most farmers are not aware of damage to their growing cereal crops if the damage is less than 5%. However, in many situations, the damage is significant and the losses will threaten the peoples' livelihoods and food security (Belmain et al., 2008; UNDP, 2009), especially with a growing world population. In these cases, management actions are needed to reduce losses to tolerable levels. Examples of the levels of rodent damage to crops around the world are presented in Table 2. Rodent damage occurs in most parts of the world and many crops and resources are involved, and damage levels can be significant, if not severe. Damage is especially severe in tropical areas and in developing countries (Meehan, 1984; Singleton, 2003).

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## MONITORING RODENT POPULATIONS

An integrated pest management (IPM) approach generally will involve several methods woven into an effective damage reduction strategy (Witmer, 2007). An important principle of IPM is pest “scouting” (Matthews, 1996). However, the monitoring of vertebrate populations (especially small, nocturnal, secretive species) is problematic (Engeman and Witmer, 2000a). Monitoring first allows one to determine the specific species of rodents that occur in the area. Several to numerous rodent species may occur in any given area, but in many situations only one species is causing the damage. Knowing what species are present is important in designing a control strategy, to allow for the complications of baiting and trapping that other rodents may cause, and to plan for minimizing non-target losses. Monitoring rodent populations also is important because densities can fluctuate dramatically within a year and between years.

Obtaining accurate estimates of population density is difficult, as well as costly, in terms of labor, time, and resource requirements. There is considerable discussion within the wildlife profession as to the importance or need for highly accurate population density estimates in IPM programs because the objective is to manage damage rather than populations. Often, an index that efficiently tracks the rodent pest population is used. The index allows documenting of changes in the population through time and space, helps define the potential magnitude and geographical extent of damage that might result from population increases, and sets the stage for the implementation of an IPM strategy. Often, monitoring of pest populations is an important component of the assessment of the efficacy of control methods. There are a number of desirable properties to consider in the selection of a wildlife population indexing methods, including some associated with the planning stage, the in-field application, and the analytical phase (Witmer, 2005).

A wide array of methods exist for monitoring rodent populations and activity, including trap grids or transects, plot occupancy, open and closed holes per unit length for burrowing species, bait station or chew card activity, food removal, and runway or burrow opening counts (Engeman and Witmer, 2000a; Witmer and VerCauteren, 2001). Ideally the indices of choice have previously been validated as a reasonable measure of changes in population size for the species and habitat of interest. Such validations are available in some instances for rodents (e.g., Quy et al., 2009). Unfortunately, a good understanding of the relationship between the population index and the actual population density, or with the amount of crop/resource damage, is an exception rather than the rule (Leirs, 2003). There are advantages and disadvantages to each index that one must carefully consider before implementation. For example, the result of many indices can vary with the soil and habitat type (complexity, amount of cover, degree of human disturbance, etc), weather conditions, and the time of year. If the aim is to determine the efficacy of a management method then it is best to use 2 or more indices. Indeed, regulatory agencies may require two indices to be used, which is the case in the USA and the UK when data sets for rodenticide efficacy are submitted to federal regulatory agencies in support of new rodenticide registrations. Damage assessments are one of the most effective means of indexing population activity and determining program efficacy.

## CHALLENGES TO MANAGING RODENT DAMAGE AND POPULATIONS

Rodents and their damage pose many management challenges. Solving rodent pest problems requires a careful consideration of:

- 1) the biology, population dynamics and seasonality of breeding of the pest species,
- 2) the ecology of the species within its physical and biotic environment,
- 3) an understanding of the relationships of the pest species to the activities of humans, including land uses, management practices, and other human activities,
- 4) the capacity (labor and financial resources) of farmers, government agencies, grain traders, etc., to implement and sustain the required management actions, and
- 5) the ecological consequences of the proposed actions (Singleton et al., 1999; Conover, 2002; Witmer, 2007).

It is only when we have adequate background knowledge in these areas that we can develop effective IPM strategies for rodent population and damage management (Figure 1). This is true because ecologically-based management requires us to focus on rodent population ecology, the environment effects for particular habitats, and the socio-economic factors that influence adoption (e.g., Witmer et al., 2003).

The traditional approaches to rodent population and damage management have relied on direct reduction of the population using rodenticide baits or rodent traps, and the reduction of habitat carrying capacity by habitat manipulation (Singleton et al., 2007a; Witmer et al., 1995). Today, many approaches focus on management efforts that are environmentally benign (Singleton et al., 1999; Pelz, 2003). Although many diverse techniques are available for rodent management (Table 3), most only provide temporary

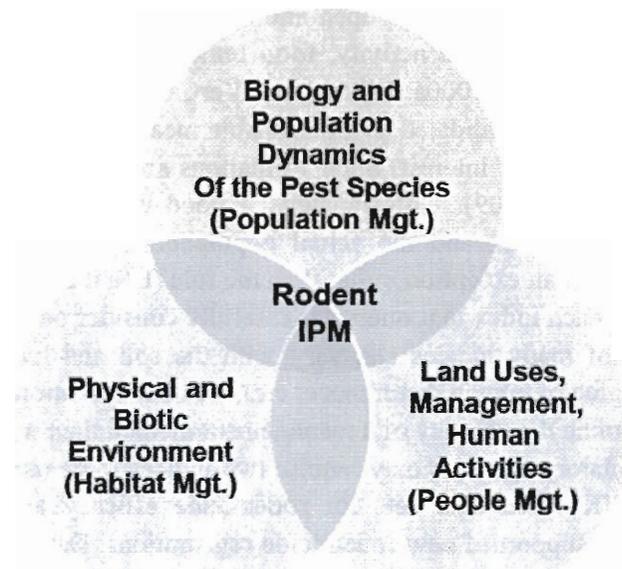


Figure 1. A triad of rodent population and damage management components that are underpinned by affordability and environmental effects.

control and/or are inhumane or adverse to the environment. Importantly, managers must consider the location, species, and type of damage before choosing an effective management strategy. Every situation can be unique and a “cookbook” approach will not suffice for every incident. Each method has advantages and disadvantages, and generally using an IPM strategy will involve several methods to reduce damage. Many governments, universities, and non-governmental organizations have compiled books or manuals on rodent control specific to particular species and regions. Some examples from around the world are listed in Table 4.

**Table 3. Methods and techniques for rodent control that have been suggested, tested, or used for various rodent problem situations (expanded from Fall, 1991).**

Physical	Chemical	Biological	Other
Rodent proof construction	Baits/baiting systems	Fertility control	Appeasement
Passive barriers	Glues	Immunogens	Insurance
Electric barriers	Poison sprays	Habitat modification	Bounties
Drift fences	Poison moats	Cultural practices	Harvest
Trapping	Tracking powder	Crop timing	Compensation
Flooding burrows	Tracking greases, gel	Crop diversification, and species selection	
Drives	Repellents	Buffer crops	
Hunting	Attractants	Parasites	
Clubbing	Aversive agents	Diseases	
Frightening devices	Plant systematics	Predators	
Flame throwers	Sterilants	Ultrasonics	
Burrow destruction	Fumigation	Biosonics	
Habitat destruction	Psychotropic drugs	Resistant plants	
Harborage removal	Herbicides	Lethal genes	
Supplemental feeding	Poisons mixed with vehicle oil applied to flooded rice	Endophytic grasses	
Digging		Unpalatable plants	
Dogs together with flooding or digging			

## POPULATION MANAGEMENT OF RODENTS

Populations of rodents can be reduced by a variety of means. While methods such as trapping, burning, flooding, and drives have been---and are still being---used in developing countries, much of the world has come to rely on rodenticide baits for rodent control (Singleton et al., 1999; Witmer et al., 1995; Witmer and Eisemann, 2007). Most rodenticides were initially derived from naturally-occurring plant materials; however, most are now produced synthetically. Rodenticide delivery to targeted rodents typically occurs through consumption by rodents. There are two general classes of oral rodenticides. Acute rodenticides (e.g., compound 1080, zinc phosphide, strychnine) usually kill following a single feed. In contrast, chronic or multiple-feed rodenticides (e.g., warfarin, coumatetralyl, pindone, chlorphacinone, and diphacinone) usually require several days of feeding before an animal ingests a toxic dose. The distinction has become somewhat blurred because chronic rodenticides includes first (examples given) and second (e.g., bromadiolone, brodifacoum,

difethialone) generation anticoagulants. Second generation compounds are very toxic and can usually kill following a single feeding, but still require several days for toxic symptoms to appear. Rodenticides can be applied in a variety of ways: hand-broadcast, aerially broadcast, placed in runways and burrows, placed near burrow openings, or placed in bait stations (Witmer and Eisemann, 2007). An additional group of rodent toxicants are the fumigants

**Table 4. Examples of books and manuals providing rodent damage management guidelines.**

Region	Title	Reference
Worldwide	Rodent Control in Agriculture	Greaves, 1982
Worldwide	Rats and Mice	Meehan, 1984
Worldwide	Control of Mammal Pests	Richards and Ku, 1987
Worldwide	Rodent Pest Management	Prakash, 1988
Worldwide	Rodent Pests and Their Control	Buckle and Smith, 1994
Worldwide	Ecologically-Based Rodent Management	Singleton et al., 1999
Worldwide	Rat, Mice and People: Rodent Biology and Management	Singleton et al., 2003
North America	Prevention and Control of Wildlife Damage	Hygnstrom et al., 1994
North America	Rodent Control	Corrigan, 2001
California USA	Vertebrate Pest Control handbook	Clark, 1994
Europe	Rodents as Pests	Putman, 1989
Africa	Rodent Pest Management in Eastern Africa	Fiedler, 1994
Africa	Rodent Biology and Integrated Pest Management in Africa	Leirs and Shockaert, 1997
Africa/Asia	Plant Protection Bulletin	FAO, 1988
Near East Asia	Rodent Pests and Their Control In the Near East	Greaves, 1989
Middle East Asia	Recent Advances in Rodent Control	Mohammad et al., 1983
India	Rodents in Indian Agriculture	Prakash and Ghosh, 1992
Bangladesh	Rodent Pests: Their Biology and Control in Bangladesh	Posamentier and Elsen, 1984
Pakistan	Handbook of Vertebrate Pest Control in Pakistan	Roberts, 1981
Pakistan	Vertebrate Pest Management	Brooks et al., 1990
Malaysia	Rodent Pests of Agricultural Crops in Malaysia	Khoo et al., 1982
South Asia	The Relative Importance of Crop Pests in South Asia	Geddes and Iles, 1991
Asia/Indonesia	Rodents and Rice	Quick, 1991
Asia/Philippines	Philippine Rats: Ecology and Management.	Singleton et al., 2008
Asia/Pacific	Field methods for rodent studies in Asia and the Indo-Pacific	Aplin et al., 2003
Australia	Managing Vertebrate Pests: Rodents	Caughley et al., 1998
Australia	MOUSER (Version 1.0): An interactive CD-ROM	Brown et al., 2003
New Zealand	The Ecology and Control of Rodents in new Zealand Nature Reserves	Dingwall et al., 1978
New Zealand	The Handbook of New Zealand Mammals (2 <sup>nd</sup> edition) – see chapters on house mice, black rat, Pacific rat and Norway rat.	King, 2005

(e.g., gas cartridges, aluminum phosphide, methyl bromide) which are used in fumigating buildings or in burrow systems that are closed after application of the fumigant.

Considerable development has gone into making rodenticides effective, efficient, and relatively safe for use in buildings and surrounding areas. There also has been progress with the development of ecologically-based baiting strategies to assure safer and more effective use of rodenticides in cropland settings (Ahmed and Fiedler, 2002; Jackson, 2001; Ramsey and Wilson, 2000). However, primary and secondary poisoning is still a concern in croplands. In many countries, the use of rodenticides is carefully regulated by national, state, and provincial governments. Authorities decide who can use rodenticides and what training and record-keeping is required, along with which rodenticides and concentrations can be used and where, when, and how they are used. Research is underway to find new rodenticides as well as ways to make existing rodenticides more effective and less hazardous to non-targets and the environment. This is especially important in light of the fact that some rodenticides are being removed from the market and there are increasing restrictions on the use of many of these compounds (Jackson, 2001; Pelz, 2003; Witmer and Eisemann, 2007). Unfortunately, there are many cases of misuse of rodenticides or illegal or unapproved use (e.g., Schiller et al., 1999). In developing countries, there can also be issues of quality control in the production and sale of rodenticides (Bruggers et al., 1995).

There are many aspects of the biology and ecology of a rodent species that must be understood in order to effectively use rodenticides (or, for that matter, even traps or bait stations). Here we will present only a few important examples. Many rodent species are neophobic, exhibiting a fear of new objects, odors or tastes in their surroundings. As such, materials may have to be placed out for a few days to allow rodents to adjust to them. Traps may have to be placed in a locked-open position and baited for a few days before they are effective in catching rodents. This is also true with bait stations which may need to be in place for several days before rodents will enter them. Some traps are more effective in catching rodents than others and this varies widely by species of rodent. There has been a long history of rodent trap development; for example, Marsh (1997) reviewed the development and production of traps for pocket gophers. Some rodents become trap-shy after an initial capture and are difficult to re-capture, while others become "trap-happy" and can be readily re-captured. This becomes an important consideration for rodent researchers using capture-mark-recapture techniques to estimate population density.

Most rodents have well developed senses of taste and smell and relatively long memories. Consequently, baits must be fresh and not moldy or rancid. Additionally, some acute rodenticides are rather unpalatable (e.g., strychnine is bitter) and others (e.g., zinc phosphide) cause sickness so quickly that the animals may become bait-shy after an initial, non-lethal exposure. To avoid this, it is sometimes necessary to pre-bait with a non-toxic base material (e.g., grain without the zinc phosphide) before applying the toxic bait to help assure that the rodents will consume a lethal dose in a single feed. This is not a problem with anticoagulant rodenticides whereby the animal slowly becomes ill over time (i.e., as internal hemorrhaging begins), but continues to feed on the toxic bait which it does not associate with the gradual onset of illness. On the other hand, some populations of rodents that have been repeatedly exposed to an anticoagulant rodenticide, such as warfarin, have become resistant to the toxicant. Anticoagulant-resistant populations require the use of a different rodenticide or a different control strategy (e.g., Pelz, 2007). It is important to identify effective rodenticides for a particular species and situation, and an effective formulation and a baiting strategy that

will effectively reduce the targeted population while minimizing non-target hazards (e.g., Cruz et al., 2008; Fan et al., 1999; Mathur, 1997; Moran, 2008; Witmer et al., 2007b).

It is also very important to recognize that rodent populations generally recover very quickly after rodenticide application (Zhong et al., 1999; Witmer et al., 2007c). Rodent populations can recover quickly even after major habitat alterations such as flooding (Zhang et al., 2007). Hence, continued applications or the use of other methods (discussed below) should be considered for the long-term control of rodent populations.

The feeding habits and food preferences of rodents may shift during the course of a year, therefore, baits used to deliver toxicants or to lure rodents into traps may have varied success depending on the seasonal preferences of the targeted rodents. For example, some rodents switch from a diet of green, succulent plant material early in the growing season to one primarily consisting of seeds once plants become senescent (Marsh, 1994).

The habitat needs, and especially cover requirements, for most rodents are critical because of the constant threat of predation, both day and night (see Ylönen et al., 2002). Knowing this, managers have tried to increase predator densities and reduce available cover as ways to reduce populations and damage. Unfortunately, prey populations usually drive predator populations, not the other way around. Artificial perches and nest boxes have been constructed to attract hawks and owls near croplands, orchards, and grasslands. Especially where natural perches were limited, these structures were used by raptors that preyed upon rodents and other animals (Ojwang and Oguge, 2003; Witmer et al., 2008a). In contrast, there is other evidence that suggests the rodent population or rodent damage is not substantially reduced as a result (e.g., Howard et al., 1985; Pelz, 2003; Sheffield et al., 2001).

Another theoretical way to reduce rodent populations is through disease agents or parasites. This approach has not yet had successes like those achieved during control for pest insect and plant populations. A major concern of using vertebrate biocides is that the agent may affect non-target species, including humans and livestock (Painter et al., 2004). This has been the case with the use of *Salmonella* spp. to control rats. A blood protozoan parasite, *Trypanosoma evansi* (Singla et al., 2003) and a liver nematode, *Capillaria hepatica* (= *Callodium hepaticum*) (Barker et al., 1991) have shown some potential for their ability to safely control rats and mice, however, the effect at the population level has not been sufficient to provide effective control. In Thailand, the protozoan, *Sarcocystis singaporensis*, is being investigated as a potential biocide (Boonsong, 1999; Khoprasert et al., 2008). A major problem is the maintenance of the disease agent or parasite in the environment after the target pest population has been greatly reduced. While there have been substantial successes with rabbit population control in Australia with the use of a myxoma virus and a rabbit calicivirus (Pech, 2000; Angulo and Bárcena, 2007), there are few success stories of biological control for mammal pest populations (see reviews by Leirs and Singleton, 2006; Baker et al., 2007).

Fertility control is often considered an attractive alternative to lethal control of rodents. There have been small-scale trials with various chemical compounds and some of these materials have shown promise (Miller et al., 1998). There are, however, many difficulties to overcome before any of these materials become available on the commercial market (Tyndale-Briscoe and Hinds, 2007; McLeod et al., 2007), including the need for an effective remote delivery system and the need to get a national, state, or /provincial registration that would allow the use of compounds in the field, especially given that the effects of such compounds would probably not be species-specific (Fagerstone et al., 2002). Using viruses as a vector for delivering species-specific sterility proteins has proven effective under laboratory

conditions but the level of natural transmission to unaffected animals has been insufficient to proceed with field trials (Redwood et al., 2007). Nonetheless, several compounds and approaches have shown promise for fertility control of rodents (German, 1985; Seeley and Reynolds, 1989; Jacob et al., 2006; Zhao et al., 2007). There has also been some preliminary investigation of the ability of altered light cycles (e.g. artificial light at night in fields) to influence vole reproduction (Haim et al., 2004).

## ECOLOGICAL RELATIONSHIPS: PHYSICAL AND BIOTIC ENVIRONMENT

Effective management of rodent pests also requires a thorough knowledge of the ecological relationships for the species in natural, semi-natural settings, and especially in human-altered settings (Leirs, 2003; Singleton et al., 2007b). For rodents, the physical environment is comprised of various structural features (e.g., soil, water bodies, rocks, plants, buildings, roads) and weather parameters. Densities of rodent populations will vary with regard to the environmental factors (e.g., soil type; Massawe et al., 2008). The biotic environment consists of all other species which can serve as competitors (e.g., other wildlife species, livestock, or humans) for food or space, or as predators (e.g., carnivores, raptors, snakes, humans). The biotic environment also includes endo-parasites, ecto-parasites, and disease organisms that can debilitate or kill rodents.

Some rodents can significantly alter their physical and biotic environment; for example, American beaver flood areas by building dams across streams or by plugging culverts, creating sizable water bodies and altering water flow regimes (Naiman et al., 1988). Also, pocket gophers can successfully prevent forest regeneration (after harvest, windstorm, or fire) by clipping and feeding on large numbers of tree seedlings (Engeman and Witmer, 2000b). On a smaller scale, rodents are very adept at creating burrow systems or sheltered nests (e.g., in trees, downed logs, or rock piles) to provide for their most basic cover needs. However, for the most part, rodents are at the vagaries of their physical and biotic environment (Batzli, 1992).

All rodents require food, shelter, and water. Availability and palatability of foods and quantity and quality of vegetative cover vary greatly between habitats and seasons, and sometimes between years (Tann et al., 1991). Consequently, rodents may switch their foraging preference and strategy during a year as well as between years. The success of many management activities directed towards rodents depend upon whether or not alternative foods are available. Additionally, rodents will often retreat to certain habitats or more sheltered areas when cover or food becomes sparse (e.g., after crop harvest; Singleton, 1989) or weather conditions become more severe. These areas serve as refugia and can act as source populations for population sustainability, increases, dispersal, or even irruptions (Elmoultie and Wilson, 2005; Giusti et al., 1996; Miño et al., 2007; Mills et al., 1991; White et al., 2003; Witmer et al., 2007c; Singleton et al., 2007b). Refugia shelter provides protection from predators and inclement weather as well as a favorable place to bear and rear their young. It has also been noted that taller vegetation generally supports higher rodent densities (Jacob, 2008; Sheffield et al., 2001; Witmer and Fantinato, 2003). Rodents also require water, but those requirements vary greatly by species. Some require no free-standing water at all and can

meet their water needs through the metabolism of solid foods or the moisture on vegetation or other surfaces.

The amount and quality of food and vegetative cover are greatly influenced by precipitation, temperatures, photo-period, and other climatic parameters. There has been some progress in predicting and modeling rodent population responses to long-term weather patterns (e.g., house mouse irruptions in Australia [Pech et al., 1999], rodents in Africa [Leirs, 1999]). Generally, there are many factors involved and we have a relatively poor understanding of the interactions and rodent responses. We can rarely predict rodent density, where or when they will and if or when the populations will crash. This is why so many of our rodent management actions have been reactive rather than pro-active. Only with a better understanding of these underlying relationships will we begin to be more successful at predicting rodent populations and damage and be able to design and implement effective pro-active strategies (Leirs, 1999; Singleton et al., 1999; Stenseth et al., 2003).

Because of complex, and often poorly understood, ecological interactions between species, a focused attack on one rodent species may result in the unexpected. For example, Sullivan and others (1998) demonstrated this in vegetation management in orchards. They found that herbicide application to ground vegetation reduced vole numbers, but at the same time increased numbers of chipmunks and deer mice. Unpredicted outcomes can also result with efforts to alter or influence predator-prey relationships. In most situations, several rodent species usually occur and these may be in strong competition with each other. Hence, when one species is controlled or removed, another species which only occurred in low numbers may become much more numerous and begin to cause damage. This affect has been noted with control or eradication of introduced rats, whereby house mice populations suddenly irrupted once a competing species was removed (Corrigan, 2001; Witmer et al., 2007a). These undesired outcomes can be managed if proposed control programs take time beforehand to examine potential demographic dynamics at different trophic levels that involve invasive alien species and the invaded communities (Caut et al., 2009).

## **INFLUENCING FOOD AND SHELTER TO REDUCE RODENT POPULATIONS OR DAMAGE**

Because rodent food and cover (i.e., vegetation) can be greatly influenced by human activities, there has been considerable development of strategies to reduce populations and damage by manipulating vegetation. Many of these manipulations are not done just to reduce rodent habitat (which may be an incidental benefit) but for other reasons such as to reduce vegetative competition with crops or trees, to reduce soil pathogens, or to prepare sites for planting. Burning, plowing, disking, herbicide application all reduce vegetative cover, at least for the short term, and usually greatly reduce rodent populations (Massawe et al., 2003; Witmer, 2007). Plowing and disking have the additional advantage of disrupting the burrows of rodents. These methods have been used extensively in reforestation, orchards, and traditional agriculture. Understandably, farmers that have implemented no-till agricultural practices to reduce erosion, water loss and improve soil fertility have continued to suffer from high populations of rodents because the soil is not disturbed to an adequate depth and plant stubble (residues) are left on the surface (Witmer and VerCauteren, 2001; Witmer et al.,

2007c). Problems from rodents are compounded when grassy refugia are left along the periphery of crop fields that rodents can make use of when crop fields are rather bare (Brown et al., 2004). Additionally, a winter food supply for rodents is created by the spilled grains of crops such as wheat, barley, and legumes (Witmer et al., 2007c).

There has been some success in the use of lure crops or supplemental feeding to reduce damage by rodents or other vertebrates. Cracked corn or soybeans have been broadcast as lure crops after drill-seeding in no-till cropland to divert voles and other rodents from feeding on newly emerged crop seedlings or digging up and feeding on planted seeds (Witmer and VerCauteren, 2001). Sunflower seeds were broadcast on forest stands subject to tree squirrel damage with a subsequent reduction in tree damage (Sullivan and Klenner, 1993). A trap-barrier-system (TBS) was developed that uses some early planted crop fields to lure rodents into them (Singleton et al., 1998; several papers in Singleton et al., 1999; 2003). The lure fields are surrounded by a rodent barrier, but there are regularly spaced openings into multiple-capture rodent traps. The rodents in the traps are collected and killed daily. In some developing countries, the rodent carcasses are used as a source of high-protein food for humans and animals (Jacob et al., 2002; Jahn et al., 1999; Singleton et al., 2007a). This TBS method has reduced rodent invasion into the surrounding crop fields that are planted 2 to 3 weeks later. Aside from this clever use of multiple capture live traps, trapping for rodents is rarely effective or efficient in reducing populations over large acreages. One exception was coordinated community actions at a village level (100-200 ha) in intensively farmed rice fields in Southeast Asia where the average farm size was generally less than 1.5 ha (Singleton et al., 2005).

Another approach to vegetation manipulation still under investigation is the use of endophytic grasses. These are grass varieties that contain an alkaloid-producing fungus that can improve the hardiness of the grass and reduce herbivory. Some preliminary studies suggest that endophytic grass fields support lower rodent densities (Fortier et al., 2000; Pelton et al., 1991). These grasses could potentially be used in a variety of settings, but might be very valuable around cropfields and orchards where grassy areas have served as a traditional refugia for rodents and, hence, a source of dispersing individuals. Other species of unpalatable plants may offer a similar approach to lowering the rodent carrying capacity of a site (Giusti et al., 1996; Witmer and Fantinato, 2003).

Rodents compete for food with a variety of herbivores, including other rodent species, other wildlife, and livestock. There is some evidence that rodent populations can be reduced by intensive cattle or sheep grazing (Hunter, 1991; Moser and Witmer, 2000). In some cases, the intensive grazing can also reduce vegetative competition with tree saplings. In addition to reducing the food available to rodents, the livestock grazing may also compact the soil and disrupt burrow systems (Witmer and Fantinato, 2003).

## EXCLUSION OF RODENTS FROM AREAS OR RESOURCES

An alternative approach to reduce or eliminate rodent damage is to exclude them from high value areas. This is an attractive option in some situations because it is a nonlethal approach and could, potentially, solve the problem on a permanent basis. Exclusion devices can be physical barriers (e.g., fencing, sheet metal, or electric wires), frightening devices,

ultrasonic or vibrating devices, or chemical repellents (Buckle and Smith, 1994; Hygnstrom et al., 1994). Unfortunately, it is very difficult to keep rodents out of an area that they want to enter. They can usually get over, around, under, or through any kind of barrier put in their way. Their small size, flexibility, agility, gnawing capability, along with their climbing and digging abilities make them a formidable adversary. They also habituate rather quickly to noxious odors, sounds, or lights (e.g., Timm, 2003). There are detailed guides available on how to rodent-proof buildings, but success is achieved only with much effort, expense, diligence, and maintenance (Corrigan, 2001; Baker et al., 1994). In open settings such as croplands or orchards, the task is much more difficult and the chance of success is much smaller. Although research in this area continues, there are few successes to report at this time (Pelz, 2003; Witmer et al., 2007c; Witmer et al., 2008b).

Short, low voltage, electric fences have been used with some success to exclude rodents from areas, but there were a number of concerns such as non-target hazards and excessive maintenance to keep the fences operating properly (Ahmed and Fiedler, 2002; Buckle and Smith, 1994; Shumake et al., 1979). Also, in Asia smallholder farmers cannot afford voltage regulators and instead some farmers directly run 220 volt power lines around their fields. This has led to deadly results not only for the rats but also for buffalo, goats and humans.

Physical barriers around individual tree seedlings have shown some success, but, again, there were concerns about cost, maintenance, and adverse effects on seedling growth (Marsh et al., 1990). Predator odors have shown some effectiveness in some trials for repelling rodents and other herbivores from areas or individual plants (Mason, 1998; Sullivan et al., 1988), but little effectiveness in other trials (e.g., Salatti et al., 1995). The sulfurous odors in predator urine, feces, glandular excretions, blood/bone meal, and putrescent eggs derived from the break-down of animal protein, all potentially serve as a cue to herbivores that a predator may be in the area and pose a threat to the herbivore (i.e., the potential prey; Mason, 1998). Another repellent that has shown some promise is capsaicin (a natural ingredient found in chili peppers), but a fairly high concentration ( $\geq 2\%$ ) of this expensive material is usually needed for a reasonable level of effectiveness (Mason, 1998). These and other compounds have shown promise as rodent repellents (Ngowo et al., 2003; Oguge et al., 1997; Pelz, 2003; Witmer et al., 2001), but broad scale field use is still in its infancy.

## **INFLUENCE OF LAND USES, MANAGEMENT PRACTICES, AND HUMAN ACTIVITIES ON RODENT POPULATIONS**

There are many things that landowners or managers can do to help reduce the risk of damage by rodents. An important first step is to familiarize themselves with the biology and ecology of the rodents (and other vertebrates that may cause damage) in the area, along with their signs of activity (burrow openings, mounds, runways, nests, tracks, droppings, gnawing patterns) and how to identify damage by those species (e.g., Hygnstrom et al., 1994). In North America, often information of this kind can be obtained at local or county extension offices or from other state/provincial or federal agencies. University wildlife damage specialists are also important sources of information. Unfortunately, in developing countries, wildlife damage management expertise is much less available (Singleton et al., 1999). A manual put together

for identifying and working with rodents in Southeast Asia and the Pacific (Aplin et al., 2003) is an important step in overcoming those shortcomings. We provide a list of books and manuals that contain considerable region-specific information on damaging rodent species, the damage they cause, and management options (Table 4).

Proper sanitation around a property can significantly reduce food and cover available to rodents (Corrigan, 2001; Singleton et al., 1999). Removing rubbish piles, uncovered garbage receptacles, wood and metal debris piles, rock piles, piles or bales of hay, heavy mown grass, silage and other exposed livestock feed, grain spills, and mature tree fruit on the ground can aid in reducing rodent populations. A reduction in the availability of water (e.g., standing water or wet areas) can help, but is often difficult to achieve in an outdoor setting. Within buildings, food sanitation and removal of water sources are very important in the management of commensal rodents (Corrigan, 2001).

In some cases, agricultural producers have some discretion in the crops or crop varieties used, timing of planting, and the location and size of specific crop fields (Hansson, 1988; Singleton et al., 1999; Brown et al., 2004). Certain crops are more likely to be damaged than others. Cereal grains are more likely to be damaged by rodents than some crops such as soybeans or sunflowers (Brown et al., 2004; Mills et al., 1991; Wolf, 1977; Witmer and Fantinato, 2003). In many cases, large mono-culture crop fields will receive less rodent damage overall with most damage occurring along the periphery of the fields (Elmoultie and Wilson, 2005; Leirs, 2003; Mills et al., 1991; Witmer et al., 2007c); although in Asia the highest intensity of rodent damage is often in the center of fields, although the reason for this is unclear (Fall, 1977). Valuable crops that are especially vulnerable to rodents should not be grown near fallow areas, grasslands, or brushy areas that support rodent populations throughout the year and which serve as refugia from which rodents can rapidly disperse into crops.

In a region that is prone to periodic and substantial rodent damage, it is beneficial to have adjoining landowners cooperate in an overall strategy of reducing activities that support rodents and in rodent control activities (Jackson, 2001; Leirs et al., 1999; Posamentier, 1997; Singleton et al., 1999). Otherwise, a landowner may suffer continuous rodent damage despite rodent control efforts because the surrounding refugia in adjacent properties. Multiple landowner cooperation can help cost-sharing for rodent management activities and materials. In some situations, national, state, or local government support is available where vertebrate damage to agricultural production is severe.

Creation of a comprehensive and effective rodent damage management strategy would benefit from implementing an ecologically-based rodent management system (EBRM) that is tailored to the pest species, agricultural system, and prevailing climatic and habitat setting (Singleton et al., 1999). Several researchers and managers have developed this approach for use in developing countries. EBRM relies on a strong ecological understanding of the target pest species and the development of specific management actions at the farming systems level (Singleton, 1997; Singleton et al., 2007a). The key to EBRM is to reduce important resources needed by rodents such as food and nesting sites at critical times of the year through habitat modifications. Examples of these modifications would be synchrony of planting of crops (an important issue in Asia where holdings are small), minimizing the height and width of irrigation level banks to prevent rats from building nests, and controlling fallow vegetation along the edges of crop fields. Rodent populations are often controlled tactically at specific times of the year in specific habitats. This may be accomplished by various means (trapping,

drives, bounties), but the emphasis is on a lower reliance on rodenticides and more community-wide approaches (Leirs, 2003; Singleton et al., 2007a). Versions of EBRM have been introduced into a number of countries to date:

- Thailand (Boonsong et al., 1999)
- China (Fan et al., 1999 ; Zhang et al., 1999 ; Zhong et al., 1999)
- Cambodia (Jahn et al., 1999)
- Lao PDR (Brown et al., 2007)
- Vietnam (Brown et al., 2006 ; Lan et al., 2003)
- Philippines (Cruz et al., 2003 ; Miller et al., 2008 ; Stuart et al., 2008)
- Indonesia (Leung et al., 1999 ; Singleton et al., 2005)
- Bangladesh (Belmain et al., 2006)
- Africa (Makundi et al., 1999)
- Australia (Brown et al., 2004)
- Europe (Pelz, 2003)

Perhaps the closest approach to EBRM in the USA was the effort of Engeman and Witmer (2000b) to predict and manage pocket gopher damage to reforestation. Similar ideas were pursued and recommended for vole control in agriculture and forestry in the USA (Witmer et al., 2009).

Examples of the kinds of management practices that farmers can implement to reduce losses to rodents were compiled by Brown and others (2004). The situation involves reoccurring but episodic house mice outbreaks in Australia with subsequent damage to various crops. Their list of recommendations included:

- Summer crop: early cultivation and weed control
- Winter crop: pre-sowing stubble management (burn), weed control
- Rice crop: stubble management (slash, graze, burn), bait stations, manage channels and banks
- Other actions: sow early, harvest cleanly, remove cover around sheds and silos, clean up grain spills, mouse-proof buildings, monitor mouse activity, bait key habitats using bait station.

Developing a rodent IPM (or EBRM) strategy requires the careful consideration of many factors (Andow and Rosset, 1990). Once the rodent species is correctly identified, it is important to monitor the status of the population and associated damage, using one or more of the many methods that exist. Is the rodent abundance related to the amount of damage that occurs and can a threshold be identified for when action should be initiated? Next, we should consider the nature of the rodent species and, its biology and ecology (particularly breeding ecology) in the setting in which the damage is occurring. How is the animal using its habitat? How is it interacting with other species? What are our actions doing to support the rodent population and to increase the amount of damage that occurs? What are our management options in terms of manipulating the rodent population, its habitat, and our activities and land use practices so that damage can be avoided or greatly reduced? What are the advantages and disadvantages of each of those management options? In general, it is best to start with the

least invasive techniques before moving to more invasive techniques (e.g., Leirs, 2003; Pelz, 2003; Singleton et al., 2007a; Witmer, 2007). Finally, how do we mold all those considerations into a comprehensive rodent IPM and EBRM strategy that we can apply to the landscape?

The rodent management strategy under consideration should be evaluated for its ability to achieve the objective of rodent damage reduction within the set of real world constraints, including method effectiveness and duration, the associated cost and benefits, the legality, the socio-political acceptability, and whether the proposed actions are environmentally benign. Of course, once we apply the strategy, we should monitor the results to see if we have achieved the desired goal of damage avoidance or reduction (i.e., not just rodent population reduction), and whether or not there were unexpected results. The key here is to undertake adaptive management; the effectiveness of the management actions in the field are reviewed annually, if possible with the end users of the management, and changes made if required. Because relatively little is known about dealing with rodent damage situations in complex landscapes (e.g., agro-ecosystems, islands invaded by rodents), we are, in essence, conducting large-scale experimental field trials (Roy et al., 2009). It is only with adequate monitoring and adaptive resource management that we can interpret and learn from those trials and, ultimately develop a comprehensive and sustainable rodent IPM strategy.

## DECISION SUPPORT SYSTEMS

In some cases, once pest population or damage threshold levels are reached, decision support systems are in place to help the landowner or manager formulate and implement a pest damage control strategy (Coulson and Saunders, 1987). Unfortunately, there are relatively few such systems available and most are simple dichotomous keys and rudimentary computer programs. There is much variability in the goals, complexity, and input and output requirements and capabilities of existing rodent decision support systems. In particular, it is important to include economic considerations in animal crop damage, including benefit:cost analyses (Brown et al., 2004; 2006; Singleton et al., 2005; Sterner, 2008).

Important components of a comprehensive rodent decision support system include an overview of the species biology and ecology, population and damage identification and monitoring, damage potential and associated factors, an evaluation of alternative management techniques and the integration of techniques, a benefit-cost analysis component, computer user "friendliness" (for computer-assisted programs), and sources of additional information. We reviewed some available packages and noted their advantages and shortcomings (Table 5). A CD-ROM called Mouser (Brown et al., 2003), developed for house mouse irruptions in Australia, is the most complete rodent decision support systems that we have encountered, containing all of the desirable components. There is a great need, however, to improve most existing decision support systems and to develop many more for other rodent species, crops, fruit trees, etc., and to tailor them specifically for sets of end users.

**Table 5. Evaluation of some small mammal decision support systems based on nine criteria.**

Decision Key No. <sup>1</sup>	1	2	3	4	5	6	7	8	9	10
Criteria <sup>2</sup>										
Biology and Ecology	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes
Monitoring	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes
Damage Potential	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes
Options	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes
Benefit:Cost	No	Yes	No	Yes	No	Yes	Yes	No	Yes	No
Default Values	N/C <sup>3</sup>	Yes	No							
Graphics	N/C	Yes	N/C	Yes	No	Yes	Yes	Yes	Yes	Yes
Save Option	N/C	Yes	N/C	No	No	Yes	Yes	Yes	Yes	N/C
Additional Information Sources	Yes	Yes	Yes	No	Yes	No	Yes	No	No	Yes

1 1=Timm, 1994a, house mice, buildings; 2=Brown et al., 2003, house mice, agricultural fields; 3=Engeman and Witmer, 2000b, pocket gophers, forestry; 4=Case and Timm, 1984, pocket gophers, alfalfa; 5=McComb, 1992, mountain beaver, forestry; 6=Salmon and Lickliter, 1983, ground squirrels, alfalfa; 7=Cox and Hygnstrom, 1993, prairie dogs, rangeland; 8=McGlinchy, 1999, possums, rabbits, all habitats; 9=Sterner, 2002, voles, alfalfa; 10=Aplin et al., 2003, rats in agricultural landscapes in Asia.

2 Important topics or modules and whether or not included in the package or publication.

3 N/C=Not Computer-assisted.

## RESEARCH NEEDS AND FUTURE PROSPECTS

Effective rodent IPM strategies and decision support systems require substantial information that only long-term research of the given species and agro-ecosystem or commensal environment can provide. Furthermore, that research must be an integration of basic and applied studies with the needs of the end users and the desired impacts clearly defined before the research begins. Adequate information can result in more effective strategies, better predictive power, greater support and acceptance by the parties providing the funding, and by the end-users (e.g., farmers). Combining all this information is important to assure the application and sustainability of new strategies (Singleton et al., 1999). Unfortunately, there is relatively little support for long-term rodent research, and, in fact, there are relatively few rodent research scientists (Barnett, 1988). This situation is especially disturbing when one considers the imperative to manage food losses to rodents in developing countries. A recent report by the World Food Program "Emergency food security assessment" in northern Laos, reported that rodent outbreaks had a major impact on food security of smallholder farmers in 4 upland provinces with:

- 74% of interviewed households reporting losses to their crops of 50-100%

- 100% rice losses were common
- Major livelihood shock for rural households who rely on their own production for food

(See <http://home.wfp.org/stellent/groups/public/documents/ena/wfp202319.pdf>)

While some new tools are being developed, many traditional tools for the control of vertebrate pests and their damage are being banned or restricted as the general public and legislators become increasingly active in land and resource management (Conover, 2002; Jackson, 2001). Examples include bans or restrictions on the use of rodenticide baits, traps, and field burning.

As suggested in the examples of this chapter, much more research is needed in both lethal and nonlethal means of resolving rodent damage in agricultural settings. For example, the prediction of rodent outbreaks so that proper measures can be taken to reduce the potential for damage would provide a valuable tool for rodent IPM (Leirs, 1999; Stenseth et al., 2003). While this is a difficult task without a detailed and time-honored data base, progress has been made in Africa (Leirs et al., 1996; Mwanjabe and Leirs, 1997), China (Zhang et al., 1999), and Australia (Pech et al., 1999; Krebs et al., 2004).

Efforts by researchers and research funding should be expanded to identify tools and strategies to reduce rodent populations and damage to agriculture (Howard, 1988b; Krebs, 1999; Witmer et al., 1995). Some areas of promising research directions include:

- Screen for varieties of crops that are less attractive to particular rodent species; or alternatively, identify varieties that are very attractive and use them to lure rodents to multiple capture traps
- Predicting rodent outbreaks/irruptions (as per house mice in Australia; Krebs et al., 2004)
- Protecting root systems from damage by tunneling rodents
- Effective rodenticides and methods to further reduce non-target animal hazards
- Unpalatable plants and endophytic grasses
- Effective and durable repellents
- Strategies for effective fertility control of rodents
- Species interactions with other native and non-native rodent species
- Food safety issues in agricultural areas, including better characterization of the losses caused by rodents to stored agricultural produce
- How integrated rodent management can influence the prevalence of rodent borne diseases that affect humans and their livestock
- Sociological studies of the factors that promote or hinder community actions that are required for effective broad scale ecologically based rodent management
- Anticipating changes to intensive cropping systems to meet increased food demands and developing management actions in accord with these changes
- Conducting active adaptive management to assist end users who themselves have changed management practices to cope with climate change
- More rigorous economic analysis of the costs and benefits of rodent IPM.

An additional concern, receiving more attention in recent years, regards who should pay for the cost of vertebrate pest population and damage management activities that benefit the general public or the agriculturalists of a region? Unfortunately, vertebrate damage, the cost of population and damage management, and management benefits are not evenly distributed across segments of the public and private sectors (Leirs et al., 1999; Posamentier, 1997). Additional research, increased public education, and increased sensitivity by public and private sector persons involved in vertebrate pest management may help resolve some of these problems.

Rodents, the damage they cause, and the diseases they transmit have plagued human populations since the beginning of civilization. There is no reason to believe that adverse interactions will not continue for the foreseeable future as these two groups vie for resources and co-evolve in natural and human-altered ecosystems, and especially in agro-ecosystems. Therein lies the challenge for practitioners of vertebrate IPM and EBRM.

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