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Chapter 13

Perspectives on Existing and Potential New Alternatives to Anticoagulant Rodenticides and the Implications for Integrated Pest Management

Gary W. Witmer

1 Introduction to Rodents and the Damage they Cause

Comprising over 1400 species worldwide, rodents are the largest taxonomic group of mammals (Nowak 1999). Rodent use of habitats is extensive and varied. Most rodent species are relatively small, secretive, prolific, adaptable, and have continuously growing incisors which require constant eroding by gnawing. 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. All rodent species have ecological, scientific, social, and/or economic values. They recycle nutrients, aerate soils, distribute seeds and spores, and affect plant succession. Some provide meat and furs for people. Several species are used in large numbers in medical research. Additionally, they provide an important prey base for many species of predatory animals.

Relatively few (perhaps 5%) rodent species around the world are serious pests. Examples of genera and species of rodents considered to be serious pests around the world were provided by Prakash (1988) and Witmer and Singleton (2012). Numerous economic and health problems can result from rodent interactions with humans. Damage can occur to agricultural crops (both in the field and to stored foods), forests and orchards, rangelands, property (structures, cables), natural resources (both faunal and floral), and disease hazards may be posed (Marsh 1988; Witmer and Singleton 2012). Singleton et al. (2003) estimated that in Asia alone, the amount of grain eaten by rodents would provide enough food to feed 200 million people for a year. When a damage situation occurs, it is very important to determine the species causing the damage, the extent of the damage, and the abiotic-biotic-cultural factors

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involved before rodent population and damage management strategies are implemented (Singleton et al. 1999; Witmer and Singleton 2012). Damage can be particularly severe when rodent population outbreaks occur (Singleton et al. 2010).

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. Additionally, they have also been especially damaging to insular ecosystems when introduced—generally accidentally or inadvertently—to islands (Angel et al. 2009; Witmer and Pitt 2012).

Despite the many methods available to reduce rodent populations or the damage they cause, rodenticides have been heavily relied upon for many decades (e.g., Witmer and Eisemann 2007; Witmer et al. 2007b). However, there has been a growing concern about the hazards posed by rodenticides. In particular, there is concern about the toxicity and persistence in tissues of anticoagulant rodenticides (e.g., Eisemann et al. 2010; Nogueira et al. 2015; Pelz 2007; Pitt et al. 2015; Proulx 2014; Rattner et al. 2012; 2014a, b). This concern is documented in many of the other chapters of this book. The objective of this chapter is to describe the alternative methods to anticoagulant rodenticides for the control of rodent populations and damage. Both lethal and non-lethal methods are described and we also discuss the value of an integrated pest management (IPM) approach or an ecologically-based rodent management approach. While the emphasis of this chapter is the United States (US), it includes examples and citations from other countries.

2 Developing an Integrated, Robust Approach to Rodent Management

While rodenticides have been heavily relied upon to control rodent populations around the world, there are many other methods available to help reduce rodent damage and to reduce their populations (Table 13.1; Buckle and Smith 2015; Caughley et al. 1998; Hygnstrom et al. 1994; Witmer and Singleton 2012). The long-term results are generally best if a variety of methods are employed, however, many practitioners prefer to use the one method they have found to be effective and cost-efficient (Baldwin et al. 2014). As with the control of weeds and damaging insects, the development and implementation of an integrated pest management (IPM) program provides the best guarantee of a sustainable control program (Witmer 2007). Reliance on a single method may lead to declining effectiveness over time as has been the case with genetic and behavioral resistance to anticoagulants in some rodent populations. This has been seen in some cases with other single method approaches, such as trap shyness or habituation to frightening devices and repellents. To help prevent these situations from developing, rodent researchers

Table 13.1. Methods and techniques for rodent control that have been suggested, tested, or used for various rodent problem situations (from Witmer and Singleton 2012)

Physical	Chemical	Biological	Other
Rodent proof construction	Baits/baiting systems	Virally-vectored fertility control	Bounties
Passive barriers	Glueboards	Immunogens	Insurance
Electric barriers	Poison sprays	Habitat modification	Harvest
Drift fences	Poison moats	Cultural practices	
Trapping	Tracking powder	Crop timing	Compensation
Flooding burrows	Tracking greases, gel	Crop diversification, and species selection	Appeasement
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			

have proposed the development and implementation of ecologically-based rodent management (EBRM; Singleton et al. 1999). An important component of this approach is the periodic monitoring of rodent populations so that appropriate action(s) can be taken before heavy damage is unavoidable (Witmer 2005). Another important aspect of EBRM is the building of community cooperation; several examples of this can be found in Singleton et al. 2003. Rodents do not recognize legal or political boundaries, so that even a well-planned rodent control program may be inefficient and doomed to poor success if surrounding landowners are not also participating in effective rodent control. This results from the high reproductive potential and effective dispersal mechanisms of many rodent species.

It should be noted that the methods listed in Table 13.1 vary substantially in their effectiveness, durability, and cost. It is important for practitioners to become experienced in the proper use of the methods and to be using the methods properly. There are some manuals and brochures/booklets available to help persons gain that insight (e.g., Buckle and Smith 2015; Hygnstrom et al. 1994; county and university cooperative extension materials).

3 Regulations, Restrictions, and International Standards

The use of certain tools and methods discussed in this chapter (and in particular, rodenticides and traps) are generally regulated by governmental agencies within a country or political boundary. These agencies assess control methods and decide which can be used, and the “when, where, and how” of their use. Additionally, the regulations and restrictions vary widely across political jurisdictions be they federal, state, provincial, county, or municipal. They also vary over time. Hence, it is important for a potential user to check with the appropriate agency(s) as to what their current options are for rodent population or damage control.

Additionally, there have been increasing concerns about the potential non-target hazards and humaneness of rodenticides and traps. Hence, regulations and restrictions have increased for many tools. For example, the U.S. Environmental Protection Agency has made more rodenticides “Restricted Use Pesticides” so that they can only be applied by certified pesticide applicators; an example of this is zinc phosphide use in the U.S. Furthermore, in the U.S., the International Association of Fish and Wildlife Agencies (2006) determined “Best Management Practices” for furbearer trapping; these apply to some rodent species trapped for their fur: nutria (*Myocastor coypus*), muskrats (*Ondatra zibethicus*), and beaver (*Castor canadensis*). Additionally, the International Organization for Standardization (IOS) has recommended methods for testing the humaneness of kill traps (ISO 1999a) and for restraining traps (IOS 1999b). However, there appears to be relatively little agreement on all these matters between countries and even between jurisdictions within a country. It has been proposed that new animal welfare standards need to be established (Lossa et al. 2007).

4 Acute and sub-Acute Oral Toxicants

Aside from the anticoagulant rodenticides (ARs), there is a number of alternative toxicants that can be used for rodent control. These include the acute and sub-acute oral toxicants and fumigants. A brief discuss these materials and their uses as well as some advantages and disadvantages follow.

The acute and sub-acute oral rodenticides are so named because these chemicals cause adverse effects in organisms much more quickly than the ARs. Depending on the chemical, this is through relatively rapid physiological disruption or organ failure. These materials include cholecalciferol (vitamin D₃), strychnine, zinc phosphide, bromethalin, and alpha-chloralose. In some countries, compound 1080 (monosodium fluoroacetate) is used as a vertebrate toxicant; however, it is no longer legal in some countries, including the US. The modes of action of these materials have been described previously (Buckle and Eason 2015; Eason et al. 2010; Timm 1994). These materials generally contain somewhat higher concentrations (0.01–2%) of the active ingredient than do the AR baits (0.025–0.005%). Like the ARs, they come in a variety of formulations for oral consumption, including pellets,

coated grain, paste baits, and sachets. Additionally, zinc phosphide also is available in a tracking powder (placed along runways or in burrows whereby the rodents walk through it and then consume the toxic powder when they groom themselves). Depending on the label instructions, these materials (like the ARs) can be broadcast, placed in burrows or bait stations, or placed along runways.

Because the acute rodenticides are highly toxic to most bird and mammal species, they pose a significant hazard to most species through direct consumption, including people (especially children), livestock, and pets. As such, great care must be taken to avoid exposure to non-target animals. This is especially important because there are no antidotes to these toxicants. On the other hand and unlike the ARs, these materials are relatively rapidly metabolized and eliminated (i.e., dissipated as gas; zinc phosphide as phosphine gas) so there is little hazard from the secondary consumption of poisoned rodents. Some consider the acute rodenticides to be more humane than the ARs because death occurs relatively rapidly after consumption of a lethal dose. This is in contrast to the slow death from AR consumption whereby the rodent slowly dies from internal--and sometimes external--hemorrhaging. On the other hand, some of the acute rodenticides result in gasping and convulsions shortly before death, which is considered by some to be signs of an inhumane death.

A disadvantage of the relatively quick onset of signs of intoxication with acute rodenticides is that the animal may associate the consumption of the toxic bait with the onset of adverse effects. As a result of this, rodents consuming a sub-lethal dose may become "bait shy" whereby they will not consume the toxic bait in the future. Also, as with the ARs, some populations of rodents have developed a resistance to the toxic effects of some acute rodenticides (e.g., strychnine).

4.1 *Alpha-Chloralose*

Alpha-chloralose is an organic compound (narcotic) evoking a rapid onset of intoxication. It was developed as a house mouse rodenticide in Europe where it is registered, manufactured and sold for use in mouse control. The products generally contain 4% active ingredient. This agent slows down several metabolic functions resulting hypothermia and death. It is most effective with smaller rodents, such as mice, because of their high surface area to body volume ratio. The LD₅₀ is about 300–400 mg/kg (Buckle and Eason 2015; Timm 1994).

4.2 *Bromethalin*

Bromethalin is a benzenamine compound. It was developed in the United States where it is registered and often used for rodents that have developed a resistance to anticoagulants. The products generally contain 0.005% or 0.01% active ingredient.

It causes the uncoupling of oxidative phosphorylation in cells of the central nervous system which eventually leads to a decrease in nerve impulse conduction, paralysis, and death. The LD₅₀ is about 2–6 mg/kg (Buckle and Eason 2015; Timm 1994).

4.3 *Cholecalciferol*

Cholecalciferol (vitamin D₃) is an organic compound causing the mobilization of calcium from bones, resulting in hypercalcemia and cardiac abnormalities, and death results from hypercalcemia in various organs. It was developed and registered in the United States and Europe, but the European registration was later dropped in preference to the second generation anticoagulants. The products generally contain 0.075% active ingredient. The LD₅₀ is about 30–40 mg/kg (Buckle and Eason 2015; Timm 1994).

4.4 *Red Squill*

Red squill (scilliroside) is a stabilized and micronized glucoside. It causes a digitalis-like action and results in heart paralysis. It was first isolated from an aquatic plant (*Urginea maritima*) in the lily family. It was first developed in Switzerland, but was later registered and used in the United States and sold to other countries as well. The product is not readily available anymore and its use has dropped substantially in preference to the second generation anticoagulants. The products generally contain 0.05% active ingredient. The LD₅₀ is about 50–200 mg/kg (Buckle and Eason 2015; Timm 1994).

4.5 *Sodium Fluoroacetate (1080)*

Sodium fluoroacetate (also known as compound 1080) was first isolated from a poisonous African plant (*Dichapetalum toxicarium*) by researchers in Europe who surmised that it might be useful as a vertebrate toxicant. The drug is rapidly absorbed in the gastrointestinal tract and blocks the tricarboxylic acid cycle which results in a build-up of citric acid and the blockage of glucose metabolism, eventually leading to convulsions and either circulatory or respiratory failure. It is toxic to a wide array of vertebrates and has been registered and used as a vertebrate toxicant in many countries, especially Australia and New Zealand. However, it has very limited current use in the United States where it is only used in livestock protection collars. Products generally contain 0.08% or 0.5% active ingredient. The LD₅₀ is about 0.1–6 mg/kg (Buckle and Eason 2015; Timm 1994).

4.6 *Strychnine*

Strychnine is a botanical compound first isolated from the poisonous seeds of a tree species (*Strychnos* spp.). It is an alkaloid antagonizing glycine and acetylcholine receptors, resulting in muscle twitching and restlessness, followed by convulsive seizures and violent spasms and death. It was developed as a rodenticide in Europe and its use increased when it could be synthesized commercially rather than extracted from seeds. Because of its high toxicity to most mammalian species, its use is limited in many countries. In the United States, there are no above ground uses allowed and it is only registered for use in rodent burrow systems, and in particular, in pocket gopher burrows. It is no longer registered for use in Europe. It is still used in Australia to help control house mouse irruptions (“plagues”). Pelleted baits generally contain 2% active ingredient, but it is also used to coat vegetables, grains and fruits at 0.5% active ingredient. The LD₅₀ is about 1.5–8 mg/kg (Buckle and Eason 2015; Timm 1994).

4.7 *Zinc Phosphide*

Zinc phosphide is an inorganic compound that is converted into phosphine which inhibits cytochrome oxidase. It was developed and first used as a rodenticide in Europe. It is perhaps the most widely used rodenticide in the world. Like strychnine, it is heavily used in Australia to control house mouse plagues. It is produced and sold in many forms: pellets, coated grains, tracking powder, and as a concentrate used to coat vegetables and fruits. Most oral baits contain 2% active ingredient. When consumed, the bait releases phosphine gas upon exposure to the moisture and acid in the stomach. Phosphine gas is highly toxic. It quickly enters the blood stream and causes heart failure and damage to various organs. Signs of intoxication include convulsions, paralysis, coma and death. The onset of intoxication is so rapid that if the animal has not consumed a lethal dose, it will recover and then will be “bait-shy” and will no longer consume the bait. Hence, it is often recommended that the area be pre-baited with uncoated grain before the coated grain is applied. The LD₅₀ is about 20–40 mg/kg (Buckle and Eason 2015; Timm 1994).

4.8 *Research on New Active Ingredient Toxicants and Combination Toxicants*

Because of the increased restrictions on rodenticide use, the loss of some products from the commercial market, the many concerns about rodenticide humaneness and non-target hazards, and the fact that some are no longer effective against the targeted rodent species, research is expanding on potential new rodenticides. This

situation applies to both the anticoagulant and acute rodenticides. Researchers are investigating new active ingredients as well as rodenticides containing two-active ingredients (i.e., an anticoagulant and an acute toxicant in one bait, but at lower concentrations than in single active ingredient rodenticides). A new active ingredient, sodium nitrite, is being evaluated as a rodenticide and as a feral pig toxicant (Blackie et al. 2014; Eason et al. 2010). However, preliminary studies suggest it may be much more effective with feral pigs than with rodents (Campbell et al. 2015; Witmer et al. 2013). Some researchers are re-visiting formerly registered active ingredients such as norbormide (Campbell et al. 2015). Some of the research efforts with potential new rodenticides have been reported by Baldwin et al. (2016, 2017), Blackie et al. (2014), Campbell et al. (2015), Eason et al. (2010), Morgan et al. (2013), Witmer and Moulton (2014), and Witmer et al. (2014a). Another recent research area that is showing good promise is the development and testing of long-term, re-setting toxin delivery systems (Blackie et al. 2014; Murphy et al. 2014; Witmer and Moulton 2016).

5 Fumigants

Fumigants are materials that when exposed to water, or are ignited, produce toxic gases. As such, some chemicals are used to kill rodents by fumigating (i.e., filling) the structure they are living in or their burrow system with poisonous gas. The mode of action of these materials is to cause death by asphyxiation or other form of respiratory failure. Fumigants include aluminum phosphide, magnesium phosphide, acrolein, the carbon/sodium nitrate contained in an ignitable cartridge, and propane gas injected into the burrow and then ignited. There is a high concentration of the active ingredient in these toxicants (generally, $\geq 56\%$). Once placed in the burrow, all burrow openings must be sealed to achieve a high degree of effectiveness. Fumigation is usually highly effective especially when soil moisture levels are fairly high; if the soils are dry and cracked, the gas may dissipate too rapidly to have its lethal effect. The methods are used in agricultural settings and around structures. However, use of the materials in structures is highly regulated or restricted because of the risk to humans, livestock, and pets. The gases produced by the fumigants rapidly dissipate so that there is generally only a short-term potentially hazardous situation. However, presumably all vertebrates in the treated burrow system would be at risk of death as well as most invertebrates present. The use of fumigants has been described by Hygnstrom et al. (1994).

6 Traps

A wide array of traps have been developed and used to manage rodents and many types are commercially available (Hygnstrom et al. 1994; Proulx 1999). Trap types are subdivided into live traps and kill traps. With live traps, the rodent becomes

contained in a box or cage trap after tripping a treadle. Another type of live trap is the leg-hold trap which, when tripped by the rodent's paw, springs the jaws of the trap to close tightly around the leg and hold the animal until the trapper or researcher arrives. Leg-hold traps are generally only used for larger rodent species such as nutria (*Myocastor coypus*), muskrats (*Ondatra zibethicus*), and beaver (*Castor canadensis*). Live traps and leg-hold traps generally can be purchased through various commercial outlets. Animals captured in live traps can be relocated (where regulations allow) to other locations or euthanized. An advantage of live traps is that non-target animals captured can often be released unharmed.

Kill traps cause the rapid death of the rodent by body constriction when the rodent trips the trap's trigger mechanism. The most common type of rodent kill trap is the snap trap. Another type of kill trap is the Conibear trap used for larger rodent species. Kill traps can generally be purchased through a variety of commercial outlets. Hygnstrom et al. (1994) provided good illustrations of various types of traps and directions for their proper and effective use. Effective trapping requires skill and practice. Using the proper type of trap for the situation, proper placement, and appropriate bait or lure is very important to achieve a high level of trap success (i.e., a high capture rate). Considerable effort has gone into identifying effective lures and baits for traps (e.g., Jackson et al. 2015; Jojola et al. 2009; Witmer et al. 2010, 2014b). A disadvantage of kill traps is they can injure or kill non-target animals, including birds. Various types of traps are also used to monitor rodent populations. Rodent population monitoring is essential so that necessary management action can be taken before populations get very large at which point extensive damage to resources cannot be avoided (Witmer 2005). Additionally, using traps over large areas is very labor intensive. However, once the rodents have been removed from a large area, often a boundary/perimeter trapping strategy can be employed to greatly slow reinvasion (Proulx 1997).

Self-resetting, multiple kill traps have been developed in New Zealand for control of invasive rats and other invasive species such as stoats (*Mustela ermine*) and brush-tailed possums (*Trichosurus vulpecula*) (Peters et al. 2014). This was, in part, to reduce the high labor costs of running trap lines which requires frequent checking and resetting. However, Warburton and Gormley (2015) determined which type of trap was more efficient: at low densities, larger numbers of single capture traps were more efficient, whereas at higher densities, fewer multiple capture traps was more efficient. Research is also underway to improve the species-specificity of self-resetting, multiple kill traps (e.g., Blackie et al. 2014; Campbell et al. 2015).

Another type of trap is the glueboard. Glueboards are a non-toxic device used to catch and hold mice, and to a lesser extent, rats. The advantages of glueboards are that they are non-toxic, non-contaminating, hold the carcass in one place, have a high capture rate for animals that encounter them, require no license for their use, and are inexpensive (Cowan and Brown 2015). On the other hand, the sticky substance in the flat trays holds the rodent until it dies, presumably from dehydration and/or starvation. Because of that slow---and presumably painful form of death---glueboards are considered inhumane by many. For that reason, some European countries have banned the use of glueboards. More recently, New Zealand banned the use of glueboards, although many exemptions are issued (Cowan and Brown

2015). Corrigan (1998) reported that glueboards weren't particularly effective with house mice. Additionally, glueboards are non-selective so that non-target animals can be captured (e.g., bats, birds, skinks). Live traps, kill traps, and rodenticides are considered the best alternatives to glueboards where they can be effectively and safely used (Cowan and Brown 2015; Corrigan 1998, 2001).

7 Barriers and Exclusion

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 include physical barriers (e.g., fencing, sheet metal, or electric wires), frightening devices, ultrasonic or vibrating devices, or chemical repellents (Buckle and Smith 2015; Hygnstrom et al. 1994). Unfortunately, it is very difficult to keep rodents out of any area that they attempt 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 small. Although research in this area continues, there are few successes to report at this time (Pelz 2003; Witmer et al. 2007c, 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 2015; Shumake et al. 1979). In Asia, small landholder 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).

8 Repellents

A number of rodent repellents have been registered by the USEPA for use in the United States, but their effectiveness is generally considered to be low. Nonetheless, considerable research effort has gone into—and continues—to identify effective repellents for rodents. 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). The product usually comes as a liquid concentrate that contains a solvent and an adhesive agent so that it sticks to the material to be protected when it is sprayed or brushed on. Recent studies have shown some other plant secondary metabolites to be effective as rodent repellents (Hansen et al. 2015; Hansen et al. 2016). While these and other compounds have shown promise as rodent repellents in cage and pen trails (Ngowo et al. 2003; Oguge et al. 1997; Pelz 2003; Witmer et al. 2001), yet to be shown is broad-scale field efficacy of rodent repellents. Some of the issues are that animals may acclimate/habituate to the materials and the effectiveness depends on how hungry the animals are and whether or not palatable alternative foods are available. In another, related research area, efforts are underway to incorporate bird repellents into rodenticides to reduce the risk of harming non-target animals (Cowan et al. 2015; Werner et al. 2011).

9 Habitat Management

Because rodent food and cover (i.e., vegetation, debris piles, food waste) can be greatly influenced by human activities, strategies have been developed to reduce populations and damage by manipulating vegetation and other features in the human-altered landscape. 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 et al. 2007c). Plowing and disking have the additional advantage of disrupting the burrows of rodents (Salmon et al. 1987). However, in some cases, disking and soil compaction have not reduced rodent numbers (Witmer and Borrowman 2012). These methods have been used extensively in reforestation, orchards, and traditional agriculture. Understandably, farms 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, Witmer 2011).

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; reviewed 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. 2007). This TBS method has reduced rodent invasion into the surrounding crop fields that are planted 2–3 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. They may also reduce rodent populations in the large grassy areas at airports. The mixture of grass and herbaceous species provides food and cover for rodents which, in turn, attracts raptors; these large birds cause a bird-aircraft strike hazard at many airports (Witmer 2011). 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 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).

Field flooding and burning are two other methods of habitat management that are sometimes used to reduce rodent populations and the habitat carrying capacity for rodents. These approaches are mainly used in agriculture areas before crop planting (in the case of flooding) or after crop harvest (in the case of burning). They are also used more so in developing countries where other methods are not readily available or affordable.

10 Encourage Natural Predation

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, farm, ranch, and natural resource managers have tried to increase predator densities and reduce available cover as ways to reduce rodent 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 such as rabbits (Ojwang and Oguge 2003; Witmer et al. 2008a); while the methods seemed to slow population growth and colony expansion, they did not prevent it completely. In contrast, there is other evidence that suggests the rodent population or rodent damage is not substantially reduced as a result of predator attraction (e.g., Howard et al. 1985; Pelz 2003; Sheffield et al. 2001).

11 Fertility Control

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 (e.g., diazacon and nicarbazin) have shown promise (Miller et al. 1998; Fagerstone 2002). There are, however, many difficulties to overcome before any of these materials become available on the commercial market (Fagerstone et al. 2010; Tyndale-Biscoe 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 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; Campbell et al. 2015). Currently, GonaCon is registered in the US for the control of over abundant white-tailed deer (*Odocoileus virginianus*) and feral horses (*Equus caballus*) and feral burros (*Equus asinus*) (Fagerstone et al. 2010). Another product, OvoControl, is registered for overabundant Canada goose (*Branta canadensis*) control (Fagerstone et al. 2010). However, no products have been registered in the U.S. for rodent fertility control, although several materials have shown promise including GonaCon and diazacon (Mayle et al. 2013; Nash et al. 2007; Yoder and Miller 2011). Several other 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). An oral delivery system is important—versus the need for injection—if a fertility control agent is to be effective and efficient method for rodent control. Ongoing research with a

palatable liquid formulation (ContraPest) has provided promising results (Dyer and Mayer 2014; Pyzyna et al. 2014; Witmer et al. 2017) and was recently registered by the USEPA for use with Norway and black rats. It should be noted that damage may still occur once animals are sterilized, but presumably, the population will be slower to increase in density and less likely to expand into unoccupied areas. Because many species of rodents are territorial, it is also presumed that the immigration of fertile individuals will not occur much until the sterile animals begin to die off. 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), although it is too soon to know if this will be an effective method of rodent population reduction.

12 Disease Agents

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 et al. 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 invasive rabbit population control in Australia with the use of a myxoma virus and a rabbit calicivirus (Pech 2000; Angulo and Bárcena 2007), there has been limited success with biological control of other mammal pest populations (see reviews by Leirs and Singleton 2006; Baker et al. 2007).

13 Research Needs and Conclusions

Additional research is needed to improve existing methods and to develop new methods for rodent detection, control, and damage reduction. Such efforts should include both lethal and nonlethal means of resolving rodent damage situations (Witmer et al. 1995; Witmer and Singleton 2012). Emphasis should include, but not be limited to, detection methods, new rodenticides, effective repellents, and

barrier development and improvement; biological control; fertility control; and habitat manipulation (Blackie et al. 2014; Campbell et al. 2015; Eason et al. 2010). It is difficult to prioritize these research areas because progress is needed in all areas (Howard 1988). Some promising new areas of rodent research include RNA interference as a species-specific toxicant, and transgenic rodents (Campbell et al. 2015). Researchers also need to identify effective commercially-available rodenticide formulations for specific locations, regions, or islands as Pitt et al. (2011) have done for rats and mice in Hawaii and Witmer and Moulton (2014) have done for the central mainland US. This is especially important for the successful eradication of invasive rodents on islands (e.g., Howald et al. 2007; Witmer et al. 2007b; Witmer and Pitt 2012). Another important research need is the evaluation of the effectiveness of combinations of techniques, given that some combinations could potentially be much more effective in the reduction of damage and may be more acceptable to the public (e.g., Baldwin et al. 2013). For example, combining sanitation and barriers (i.e., limiting rodent access) may lessen the amount and frequency of use of traps and toxicants.

Rodents will continue to pose challenges to land and resource managers, commodity producers, and homeowners (e.g., Capizzi et al. 2014; Witmer and Singleton 2012). Many tools are available to reduce rodent populations and associated damage. They should be used in a designed IPM program. Rodenticides will continue to be an important tool to control rodents and their damage, but care must be exercised in their use. It is probably safe to assume that much of the public will continue to be leery of toxicant use. Hence, public education will be important to ensure continued availability of rodenticides. Continued technology development and transfer are essential to improve the effectiveness and safety of rodenticides and other methods used to control or eradicate invasive rodents as well as native rodents causing damage.

Additionally, seabird populations, sea turtle populations and other island resources warrant protection from invasive rodents. The recovery of fauna and flora on uninhabited islands after a successful rodent eradication is particularly notable (Witmer et al. 2007a, Witmer and Pitt 2012). The significant impacts of introduced rodents on native flora and fauna have been repeatedly demonstrated. Invasive rodents are very adaptable, can exploit a wide array of resources as food and cover, and can increase reproduction very quickly when and where abundant resources exist (Macdonald et al. 1999). While invasive rodents and commensal rodents will continue to pose challenges to land and resource managers, they can be controlled or even eradicated with a well-planned and adequately-supported effort using rodenticides and other tools. With proper planning, non-target losses will be minimal and these populations, along with other island and mainland resources, will often recover quickly after the invasive and commensal rodents have been removed (Croll et al. 2016; Le Corre et al. 2015; Newton et al. 2016).

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