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Synthesis

The changing role of rodenticides and their alternatives in the management of commensal rodents

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Abstract: Rodents cause substantial damage and losses of foodstuffs around the world. They also transmit many diseases to humans and livestock. While various methods are used to reduce damage caused by rodents, rodenticides remain an important tool in the toolbox. However, like all tools, rodenticides have advantages and disadvantages. Several considerations are shaping the future of rodenticide use, including manufacturing and registration costs, concern about toxicity levels and nontarget animal hazards, potential hazards to children, reduced effectiveness of some formulations, and humaneness to the targeted rodents. Many of these disadvantages apply to anticoagulant rodenticides, and their use is being more restricted in numerous settings. This paper discusses rodenticide use but also alternative control methods such as traps, exclusion, habitat management, repellents, and fertility control. While there have been relatively few new developments in rodenticides and other rodent control methods in the last several decades, new formulations and active ingredients are being investigated so that these concerns can be addressed. Some of these new developments and research results are also discussed.

Key words: damage, fertility control, habitat management, pesticide regulation, repellents, risk mitigation, rodent, rodenticides, traps

COMPRISING OVER 1,400 species worldwide, rodents are the largest taxonomic group of mammals (Nowak 1999). Rodents also exhibit a range of ecological plasticity in that they inhabit a wide and most extensive range of global landscapes. 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 (Lund 2015, Macdonald et al. 2015). 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 (e.g., Dickman 1999). Some provide meat and furs for people. Several species are used in large numbers in medical and other research. Additionally, they provide an important prey base for many species of predatory animals (Witmer and Singleton 2012).

Relatively few (perhaps 5%) rodent species around the world are considered economically and environmentally pests (Prakash 1988, Witmer and Singleton 2012). Globally, in low resource areas where commensal rodents may interact with humans regularly, zoonoses rates exceed actuary averages (Gebreyes et al. 2014). Economic losses can occur when rodents damage agricultural crops (both in the field and to stored foods), forests and orchards, rangelands, property (structures, cables), and natural resources (both faunal and floral; Witmer and Singleton 2012; Figure 1). Singleton et al. (2003) estimated that in Asia alone, the amount of grain eaten by rodents would feed 200 million Asians for a year.

When damage occurs, it is paramount to determine the species causing the damage, the extent of the damage, and the abiotic-biotic-cultural factors 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, Witmer and Proulx 2010).

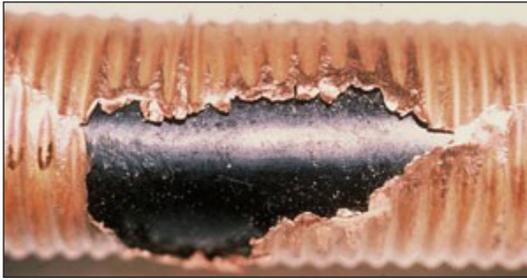


Figure 1. Rodent damage to a cable (photo courtesy of U.S. Department of Agriculture).



Figure 2. Norway rat (*Rattus norvegicus*; photo by J. Jeffery).



Figure 3. House mouse (*Mus domesticus*, *M. musculus*; source of photo unknown).

The commensal rodents include the Norway rat (*Rattus norvegicus*; Figure 2), the ship or black rat (*R. rattus*), the Polynesian rat or kiore (*R. exulans*), and the house mouse (*Mus musculus* and *M. domesticus*; Witmer and Shiels 2018; Figure 3). These species live in close proximity to humans, exploiting the favorable conditions that are created for them. Concomitantly, all the species except the Polynesian rat have spread throughout most of the world and now cause significant losses of stored foodstuffs through consumption and contamination as well as increased human health and safety concerns (Meerburg et al. 2009, Witmer and Shiels 2018). Additionally, they have also been especially damaging to insular ecosystems when introduced to islands (Angel et al. 2009, Witmer and Pitt 2012).

Despite alternative methods available to reduce rodent populations and the damage they cause, rodenticides remain the preferred control option for many decades (e.g., Witmer and Eisemann 2007, Witmer et al. 2007a). However, public concerns are increasing regarding the potential hazards posed by rodenticides, including hazards to humans, nontarget animals, and the environment (e.g., van den Brink et al. 2018). In particular, there is concern about the toxicity and persistence in tissues of anticoagulant rodenticides (e.g., Pelz 2007; Eisemann et al. 2010; Rattner et al. 2012, 2014; Nogueira et al. 2015; Pitt et al. 2015).

The objective of this synthesis paper is to review the various contemporary methods available for the control of commensal rodent populations and damage. I describe both lethal and nonlethal methods and discuss their value in an integrated pest management (IPM) approach. While the emphasis of this paper is on the U.S. experience, I have included examples and citations from other countries.

Integrated commensal rodent management

While rodenticides have been heavily relied upon globally to control rodent populations, there are many rodent damage and population reduction strategies (Table 1; Hygnstrom et al. 1994, Caughley et al. 1998, Corrigan 2001, Witmer and Singleton 2012; Buckle and Smith 2015). Long-term damage mitigation and population results are generally best achieved if a variety

Table 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 (often combined with clubbing)	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			

of methods are employed (e.g., Baldwin et al. 2019). However, many practitioners prefer to use the 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 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 urban 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.

An important but often overlooked component of rodent management is the periodic monitoring of rodent populations so that appropriate action(s) can be taken before the damage becomes excessive (Witmer 2005). Another important aspect of rodent control is the building of community cooperation.

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 (e.g., Jahn et al. 1999, Singleton et al. 1999). This results from the high reproductive potential of several rodent species in some areas and effective dispersal mechanisms of many rodent species.

The methods identified in Table 1 vary substantially in their effectiveness, durability, and cost. Also, these methods have been developed for a wide array of rodent species, and many would not be useful for commensal rodents. Thus, 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, brochures, and booklets available to help persons gain that insight (e.g., Hygnstrom et al. 1994, Corrigan 2001, Buckle and Smith 2015, county and university cooperative extension materials).



Figure 4. Rodenticide bait block (photo courtesy of U.S. Department of Agriculture).

Regulations and restrictions

The use of certain tools and methods discussed in this paper (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 agencies as to what their current options are for rodent population or damage control.

Additionally, there have been increasing concerns about the potential nontarget hazards and humaneness of rodenticides and traps. Hence, regulations and restrictions have increased for many tools. For example, the U.S. Environmental Protection Agency (EPA) 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 and second-generation anticoagulant use in the United States (e.g., Hornbaker et al. 2012).

Oral toxicants

The most commonly used oral rodenticides are the anticoagulants (Buckle and Smith 2015). The first anticoagulant, warfarin, was developed many decades ago in the United States. It, along with several that followed (pindone, chlorophacinone, diphacinone), are known as

the first-generation anticoagulants. The mode of action of anticoagulants is to shut down the body’s ability to clot blood; hence, the rodent dies slowly from internal—and sometimes external—hemorrhaging. Over the years, they became less effective, mainly because rodent populations developed a genetic resistance to them (Pelz and Prescott 2015).

This led to the development of the second-generation anticoagulants (bromadiolone, brodifacoum, difethialone; Buckle and Eason 2015). These materials are much more toxic than the first-generation anticoagulants. Rodents have to feed on first-generation anticoagulants for several days before consuming a lethal dose, whereas they can consume a lethal dose of a second-generation anticoagulant in a single feeding. However, the time to death (generally 5+ days) is the same for both generations of anticoagulants. The second-generation anticoagulants also persist much longer in tissues, which results in a higher secondary hazard to nontarget animals (especially raptors and carnivores) that consume dead or dying rodents. Anticoagulants have long been under attack because of the secondary hazards and what is considered by many as an inhumane form of death (e.g., van den Brink et al. 2018). On the plus side, there is an antidote (vitamin K) that can be administered in case of accidental consumption of an anticoagulant.

Aside from the anticoagulant rodenticides, there are a number of alternative toxicants that can be used for rodent control. These include the acute and sub-acute oral toxicants. The acute and sub-acute oral rodenticides are so named because these chemicals cause adverse effects in organisms much more quickly than the anticoagulants. 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. More specific information on the acute rodenticides can be found elsewhere (Timm 1994, Eason et al. 2010, Buckle and Eason 2015).

In some countries, compound 1080 (monosodium fluoroacetate) is used as an acute vertebrate toxicant; however, it is no longer legal in some countries, including the United States (Witmer and Eisemann 2007). These

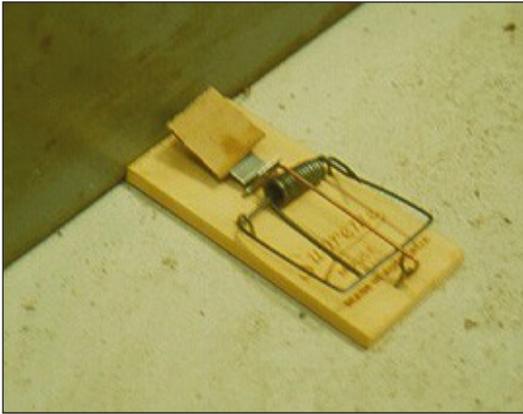


Figure 5. House mouse snap trap placed along wall (photo courtesy of U.S. Department of Agriculture).

materials generally contain somewhat higher concentrations (0.01–2%) of the active ingredient than do the anticoagulants (0.005–0.025%). Like the anticoagulants, they come in a variety of formulations for oral consumption, including blocks (Figure 4), pellets, coated grain, paste baits, liquids, and sachets (like a tea bag). Additionally, zinc phosphide also is available in a tracking powder (placed along walls, 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 anticoagulants) can be broadcast, placed in burrows or bait stations, or placed along runways as detailed on the EPA pesticide label (Witmer and Eisemann 2007).

Because the acute rodenticides are highly toxic to most bird and mammal species, they pose a significant hazard to most species through direct consumption (i.e., a primary hazard), including people (especially children), livestock, and pets (e.g., van den Brink et al. 2018). As such, great care must be taken to avoid exposure to nontarget animals. This is especially important because there are no antidotes to these acute toxicants. On the other hand, and unlike the anticoagulants, these materials are relatively rapidly metabolized and eliminated (e.g., zinc phosphide dissipates 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 anticoagulants because death occurs relatively rapidly after consumption of a lethal dose (e.g., Hadidian et

al. 2014). 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 (Hadidian et al. 2014).

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 (Macdonald et al. 2015). As a result of this, rodents consuming a sublethal dose may become bait shy, whereby they will not consume the toxic bait in the future. Some rodents learn from cohorts to avoid some rodenticides. As with the anticoagulants, some populations of rodents have developed a resistance to the toxic effects of some acute rodenticides (e.g., calciferols and strychnine; Buckle and Eason 2015).

Traps

A wide array of traps has been developed and used to manage rodents, and many types are commercially available (Hygnstrom et al. 1994, Corrigan 2001). 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. Kill traps and live traps 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 nontarget animals captured can often be released unharmed. However, target and nontarget animals released far away from the capture site may experience high mortality rates after being put in an unfamiliar environment.

Kill traps generally, but not always, 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 for commensal rodents is the snap trap (Figure 5). 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). This is especially important because some species of rodents can

be difficult to capture (e.g., nutria [*Myocastor coypus*]; Jojola et al. 2009). Considerable effort has gone into identifying effective lures and baits for traps (e.g., Jojola et al. 2009; Witmer et al. 2010, 2014b; Jackson et al. 2016).

Self-resetting, multiple kill traps have been developed in New Zealand for control of invasive rats and other invasive species such as non-rodent 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 for killing invasive vertebrates: at low densities, larger numbers of single capture traps were more efficient, whereas at higher densities, fewer multiple capture traps were 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).

A disadvantage of kill traps is they can injure or kill nontarget 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). Unfortunately, using traps over large areas (e.g., agricultural areas) is very labor intensive.

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 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 were not particularly effective with house mice. Live traps, kill traps, and rodenticides are considered the best alternatives

to glueboards where they can be effectively and safely used (Corrigan 1998, 2001; Cowan and Brown 2015).

Barriers and exclusion

An alternative approach to reduce or eliminate rodent damage is to exclude them from high value areas (e.g., Singleton et al. 1999). 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 (Marsh et al. 1990, Hygnstrom et al. 1994, Buckle and Smith 2015).

Unfortunately, it is very difficult to keep rodents out of any area that they strive to enter. They can usually get over, around, under, or through any kind of barrier put in their way. Their small size, flexibility, agility, and 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 (Baker et al. 1994, Corrigan 2001). 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 (Witmer et al. 2007b, 2008a).

Repellents

A number of rodent repellents have been registered by the EPA for use in the United States, but their effectiveness is generally considered to be low (e.g., Witmer et al. 2016). Nonetheless, considerable research effort has gone into and continues to identify effective repellents for rodents (e.g., Baldwin et al. 2018). For example, Baldwin et al. (2018) showed that anthraquinone reduced damage to citrus seedlings by voles (*Microtus* spp.). Predator odors have shown some effectiveness in some trials for repelling rodents and other herbivores from areas or individual plants (Sullivan et al. 1988, Mason 1998) but had little effectiveness

in other trials (e.g., Salatti et al. 1995). The sulfurous odors in predator urine, feces, glandular excretions, blood and bone meal, and putrescent eggs derived from the breakdown 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, 2016; Jackson et al. 2016). While these and other compounds have shown promise as rodent repellents in cage and pen trials (Oguge et al. 1997, Ngowo et al. 2003), yet to be shown is broad-scale field efficacy of rodent repellents. Some of the issues are that animals may acclimate or habituate to the materials, and the effectiveness depends on how hungry the animals are and whether 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 nontarget birds (Werner et al. 2011, Cowan et al. 2015).

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 (Witmer and Singleton 2012). 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. Mowing, burning, plowing, disking, and herbicide application all reduce vegetative cover, at least for the short term, and usually greatly reduce rodent populations (Massawe et al. 2003; Witmer 2007b, 2011; Baldwin et al. 2019).

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. 2007b). 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 and when livestock feed is available (Witmer et al. 2007b).

Increased 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 (Witmer et al. 2008b). 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. 2008b); while the methods seemed to slow population growth and colony expansion, it 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 (e.g., Howard et al. 1985, Sheffield et al. 2001, Pelz 2003). Many landowners and agriculturists have free-ranging cats on their property, but it is important to realize that cats catch and kill a large number of songbirds (e.g., Blancher 2013).

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 (McLeod et al. 2007, Tyndale-Briscoe and Hinds 2007, Fagerstone et al. 2010), 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 United States for the control of overabundant white-tailed deer (*Odocoileus virginianus*), feral horses (*Equus caballus*), and feral burros (*Equus asinus*; Fagerstone et al. 2010). Another product, OvoControl, is registered for overabundant pigeons (*Columba livia*) and Canada goose (*Branta canadensis*) control (Fagerstone et al. 2010). Several materials have shown promise for rodents, including GonaCon and diazacon (Nash et al. 2007, Yoder and Miller 2011, Mayle et al. 2013), but these have not yet been registered for rodent control.

Researches in countries outside the United States have identified several other compounds and approaches that 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 an injection—if a fertility control agent is to be an effective and efficient method for rodent control. Ongoing research with a palatable liquid formulation has proven effective with commensal rats (Dyer and Mayer 2014, Pyzyna et al. 2014, Witmer et al. 2017), and the EPA recently registered this material, ContraPest, for commensal rat control in the United States. 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.

Research on new active ingredients 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 nontarget hazards, and the fact that some are no longer effective against the targeted rodent species, research is expanding on potential new rodenticides as described below. This situation applies to both the anticoagulant and acute rodenticides. Researchers are investigating new active ingredients as well as rodenticides containing 2 active ingredients (i.e., an anticoagulant and an acute toxicant in 1 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 (*Sus scrofa*) toxicant (Eason et al. 2010, Blackie et al. 2014). However, preliminary studies suggest it may be much more effective with feral pigs than with rodents (Witmer et al. 2013, Campbell et al. 2015).

Some researchers are revisiting formerly registered active ingredients such as norbormide (Campbell et al. 2015). Some of the research efforts with potential new active ingredients or combinations of active ingredients (e.g., cholecalciferol combined with diphacinone or brodifacoum) have been reported by Eason et al. (2010), Morgan et al. (2013), Blackie et al. (2014), Witmer and Moulton (2014), Witmer et al. (2014a), Campbell et al. (2015), and Baldwin et al. (2016, 2017). Another recent research area showing 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).

Research needs

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 (Howard 1988, 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 (Eason et al. 2010, Blackie et al. 2014, Campbell et al. 2015). It is difficult to prioritize these research areas because progress is needed in all areas. 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 United States. This is especially important for the successful eradication of invasive rodents on islands (e.g., Howald et al. 2007, Witmer et al. 2007a, 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.

Conclusions

Rodents will continue to pose challenges to land and resource managers, commodity producers, and homeowners (e.g., Witmer and Singleton 2012, Capizzi et al. 2014). 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 commensal and invasive rodents as well as native rodents causing damage.

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