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Ecology, Impacts, and Management of Invasive Rodents in the United States

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Gary W. Witmer and Aaron B. Shiels

CONTENTS

INTRODUCTION TO INVASIVE RODENTS

Approximately 42% of all mammalian species in the world are rodents, amounting to about 2277 species (Wilson and Reeder 2005). Rodents have adapted to all lifestyles: terrestrial, aquatic, arboreal, and fossorial (underground). Most 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 life span, requiring constant gnawing to keep the incisors sharp and at an appropriate length. This can result in extensive damage to seeds, fruits, field crops, structures, wires, and insulation. 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 these characteristics make many rodent species ideal invaders.

Rodents have ecological, scientific, social, and economic values (Witmer et al. 1995; Dickman 1999). 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. Hence, the indiscriminate removal of native rodents from ecosystems, including agroecosystems, is not the best management option in many cases (Villa-Cornejo et al. 1998; Aplin and Singleton 2003; Brakes and Smith 2005).

FIGURE 10.1 Introduced rodents, such as this Norway rat (*Rattus norvegicus*), can cause extensive damage to island flora and fauna and to agricultural production. (Photo by Jack Jeffrey.)

Introduced rodents, whether purposefully or accidently introduced, have caused serious impacts to native flora and fauna, agriculture, property, and other resources (Capizzi et al. 2014). Long (2003) reviewed the many rodent introductions around the world and briefly discussed the resultant damage. As invasive species, rodents are particularly problematic because they have many characteristics that make them effective invaders (e.g., Pitt et al. 2011a), and as a result, numerous invasive rodents have become established in parts of the United States and its territories (Figure 10.1). By far the prominent invasive rodents in the United States are species of *Rattus* (*R. exulans, R. norvegicus,* and *R. rattus*) and the house mouse (*Mus musculus*); the Gambian giant pouched rat (*Cricetomys gambianus*) is also a formidable concern as they have established and become invasive in Florida. Nutria (*Myocastor coypus*) are among the most-damaging invasive rodents in the United States (Witmer et al. 2012a), but because of their aquatic lifestyle they are not covered in this terrestrially focused book. While this chapter focuses on *Rattus*, house mice, and Gambian giant pouched rats, there are several additional introduced terrestrial rodents that have become locally or regionally invasive in the United States, and these include hoary marmots (*Marmota caligata*), arctic ground squirrels (*Spermophilus parryii*), eastern fox squirrels (*Sciurus niger*), and eastern gray squirrels (*Sciurus carolinensis*). While fox squirrels and eastern gray squirrels were presumably introduced accidently into states and regions outside their native range, arctic ground squirrels (*Spermophilus parryii*) and hoary marmots (*Marmota caligata*) were introduced to Alaskan islands for food or fur. Additional native species of rodents (voles, *Microtus* spp. and deer mice, *Peromyscus* spp.) have been placed on some islands of the United

States, at least on a temporary basis, to study interactions among rodent species (e.g., Crowell and Pimm 1976; Crowell 1983).

In this chapter, we review the most prominent rodent species introduced into terrestrial ecosystems in the United States, and discuss their impacts to humans and ecosystems, management strategies, and the methods used to reduce invasive populations and their impacts. We also review invasive rodent eradication projects and methods used in the United States.

ISSUES AND DAMAGE CAUSED BY INVASIVE RODENTS

Several types of damage have been caused by introduced rodents in the United States (Hygnstrom et al. 1994; Witmer and Singleton 2010). The substantial and worldwide loss of human food, both standing crops and stored foodstuffs, has been documented in several reviews (Meerburg et al. 2009b; Witmer and Singleton 2010). In addition to consuming human foods, rodents also contaminate much more stored food through defecation and urination. Rodents also transmit many diseases to humans, companion animals, and livestock (Meerburg et al. 2009a). For example, the plague bacteria, *Yersinia pestis*—causal agent of the Black Death which killed millions of humans worldwide in several pandemics—reached North America in the late 1800s via infected rats on ships arriving in California ports (Witmer 2004).

Rodents can be prolific on islands where they have few or no predators. Their high reproductive potential, omnivorous foraging strategy, and aggressive predatory behavior have led to the endangerment or extinction of numerous native island species, especially birds (Moors and Atkinson 1984; Witmer et al. 1998; Veitch and Clout 2002; Engeman et al. 2006; Towns et al. 2011). While their impacts to seabirds have been long known, invasive rodents also impact seeds and seedlings, invertebrates, sea turtle eggs and hatchings, and other parts of the ecosystem (Witmer et al. 2007a; Caut et al. 2008; Angel et al. 2009; Towns et al. 2009; St Clair 2011; Drake et al. 2011). Most seabirds and many endemic land birds that nest on islands have not evolved to deal with mammalian predators and can be highly vulnerable to predation from introduced rodents and other nonnative predators. In addition to direct effects, rodents can have many indirect effects on island resources through competition and trophic cascade effects (Russell 2011). Invasive rodents have reached over 80% of the world's island groups where they have caused the demise of hundreds of endemic species (Atkinson 1985). As a result, there has been a concerted worldwide effort to eradicate introduced rodents from islands, with numerous successes (Howald et al. 2007; Witmer et al. 2011). These efforts have used a combination of techniques but relied heavily on the use of rodenticides (Howald et al. 2007; Witmer et al. 2007b).

BIOLOGY, ECOLOGY, AND DAMAGE OF SOME INVASIVE RODENTS

Norway rats (*Rattus norvegicus*; Figure 10.1) are native to a large part of Asia, but now occur worldwide with the exception of the polar regions (Long 2003). They were most likely first introduced to North America via transatlantic shipping beginning in the 1700s (Brooks 1973; Meehan 1984) but are now well established in both rural and urban areas throughout the United States, including Alaska, Hawaii, and all territories. This species is one of the most successful invasive vertebrates in the United States and is responsible for a variety of types of damage to crops and stored commodities (Jackson 1977; Timm 1994a). Norway rats likely spread rapidly and systematically across the country in conjunction with shipping of commodities and along wagon, riverboat, and rail routes. One of the three common commensal rodent species on the North American continent, the Norway rat is closely tied to human settlements.

Norway rat pelage is typically brown above, with the ventral region lighter brown/yellow or gray. The tail is sparsely haired and scaly and typically about the same length as the body. Adult body weights range from 200 to 500 g. Breeding may occur throughout the year, depending on conditions. Females produce litters of six to 12 young and are known to bear four to six litters per year (Timm 1994a). Gestation is about three weeks, and animals reach sexual maturity approximately three weeks after birth (Timm 1994a). Given their reproductive potential, populations can expand rapidly when food, water, and habitat are available.

In farm settings, damage to stored food and grains, damage to garden crops, and predation on eggs and baby chickens are common. Grain consumption and fecal contamination are common problems in commercial grain storage facilities (Jackson 1977). Damage to roads, bridges, railroad track beds, and hydraulic structures may result from burrowing activities and the associated soil loosening or flooding (Timm 1994a). Structural damage in buildings results from gnawing and burrowing and may include damage to doors, window sills, and walls as well as to pipes and wiring. Insulation may be damaged or removed in the course of nest building. In urban areas, Norway rat populations are commonly associated with poor sanitation or accumulation of trash and food refuse in inner-city areas, although outdoor feeding of pets and wildlife often supports suburban populations as well. Norway rats serve as reservoirs of a number of diseases that may affect humans and domestic animals, most commonly salmonellosis, leptospirosis, and trichinosis (Meehan 1984). In areas with high rat populations in close association with humans, rat bites may occur, particularly to babies or young children.

Management of Norway rats appears to be best achieved with habitat manipulations. Davis (1953) demonstrated that wild, free-ranging urban populations could be completely managed by environmental control and sanitation. However, Fall and Jackson (1998) contended that the political impossibility of maintaining diligence by urban residents and sustained support by public and private sectors has allowed Norway rat problems to continue unabated. Numerous products are available commercially to property owners for Norway rat control, and extensive professional rodent control services are available through the pest control industry (Timm 1994a; Corrigan 2001).

Roof rats (*Rattus rattus*; Figure 10.2), also known as black rats or ship rats, are native to a large portion of Asia, probably throughout the Indo-Malayan region and through southern China (Long 2003). They also are now widespread worldwide and are the dominant *Rattus* species found on tropical islands. Roof rats are the most successful of the three commensal *Rattus* species. In the United States, they occur in and along port and shore areas in southeastern and western North America and throughout Hawaii and tropical and temperate Atlantic and Pacific Ocean islands. Although known most commonly as a commensal species closely tied to people

FIGURE 10.2 Roof rat in native Hawaiian forest. Note the metal ear tag on the characteristically large ears. (Photo by Aaron Shiels.)

and their movements, roof rats, particularly in warmer areas, readily establish in undeveloped areas, including native forests in Hawaii and on oceanic islands (Shiels et al. 2014). According to Brooks (1973), roof rats were well established in Virginia in the early 1600s and in North America's east coast areas by the 1800s. They occur sporadically in warmer inland areas but rarely persist. However, a recent infestation discovered in urban Phoenix, Arizona raised concerns that the species could permanently establish in patches of suitable habitat and subsequently threaten crops and orchards (Nolte et al. 2003). In cooler temperate areas, roof rats compete poorly with the larger and more aggressive Norway rat, and occur mostly in port areas and generally indoors (Meehan 1984). However, in island natural areas, particularly forests, roof rats have been identified as the most destructive rodent to native species and ecosystems (Ruffino et al. 2009; Traveset et al. 2009; Banks and Hughes 2012; Shiels et al. 2014).

The roof rat pelage is reddish-brown, brown, gray, or black with the ventral area being lighter or white. The tail is generally about 27 mm longer than the body (Shiels et al. 2014). Adult roof rats weigh 150–250 g on continents, but some adults on islands in the Pacific (Shiels et al. 2014), including Hawaii (Shiels 2010), weigh just 90 g. As in Norway rats, breeding may occur throughout the year if resources are available; the pattern of breeding and the reproductive potential are similar between roof rats and Norway rats. Roof rat females typically bear three or more litters with five to eight young per litter each year (Marsh 1994). They are sexually mature by one to two months and may have a life expectancy of around one year. The typical life span for a roof rat in the wild is one year or less (Shiels 2010). Like many rodent species, they are primarily nocturnal, although when densities are high, such as on some tropical islands, they also are often active during the day.

Recently, a variant of *Rattus rattus*, the Asian house rat, has been separated taxonomically as *Rattus tanezumi* (Musser and Carleton 2005). Animals of both species are generally similar in appearance; however, *R. tanezumi* appears more variable and has a somewhat shorter tail. A chief distinguishing feature is a differing number of chromosomes between the two species, but this is of course not evident without use of special laboratory techniques, and some authorities have not accepted the name change. *Rattus tanezumi* has recently been reported as a new invasive species in North America based on collections in California (James 2006). However, species in this complex are difficult to separate morphologically. Additional molecular evidence shows that what has historically been identified as *Rattus rattus* is actually a complex of approximately five to seven species (Robins et al. 2007; Pages et al. 2010).

Like the Norway rat, the roof rat invades homes and structures, causing damage and contamination of stored food and commodities (Marsh 1994). However, it survives well in field and forest habitats in tropical and subtropical areas (Shiels et al. 2014) and causes damage to orchard, grain, and sugarcane crops in such states as California and Hawaii (Kami 1966; Baldwin et al. 2014). Because of their arboreal nature, roof rats can prey on adult birds, nestlings, and eggs. Furthermore, they are recognized worldwide as the likely cause of rare bird extinctions in many island areas, including Hawaii (Munro 1945; Atkinson 1977; Pitt and Witmer 2007). Roof rats are well-known predators of seabirds, especially those that are ground- and burrow-nesting (Jones et al. 2008) and especially small-egged species. Latorre et al. (2013) demonstrated that although roof rats were able to consume all sized eggs offered (12–68 g), larger eggs were 13 times more likely to survive roof rat interaction than the smallest eggs. Roof rats also eat native and nonnative snails, and in Hawaii they depredate the introduced predatory snail, *Euglandina rosea*, which has complicated management strategies to protect native tree snails (Meyer and Shiels 2009). Roof rats also pose substantial threats to native and endangered plants through seed predation (Pender et al. 2013; Shiels and Drake 2015), as well as potentially aiding in the spread of nonnative seeds via dispersal (Shiels 2011; Shiels and Drake 2011). Although the majority of the roof rat diet in island natural areas is plant material (Shiels and Pitt 2014; Shiels et al. 2014), insects comprise the second most common food item (Shiels et al. 2013), which reveals their link to potential impacts on additional ecosystem services such as pollination and decomposition (St Clair 2011).

Roof rats are a reservoir for a number of diseases of humans and animals, but are most notorious for their role in bringing bubonic plague, the "Black Death," to 14th century Europe. The occurrence of bubonic plague in Hawaii during 1899 to 1958 was associated with this species (Tomich 1986), as were the initial outbreaks in California in the early 1900s (Witmer 2004). While roof rats rarely transmit plague today, they are known to transmit other bacteria that negatively affect humans, such as leptospirosis, and transmit several types of harmful nematodes, including *Capillaria hepatica* (Berentsen et al. 2015) and *Angiostrongylus cantonensis* (Wang et al. 2008). Rat lung-worm disease, which is caused by *A. cantonensis* nematodes infecting the human brain and causing symptoms ranging from severe headaches to coma and death (Wang et al. 2008), is particularly known in the United States in wet regions of Hawaii (Jarvi et al. 2015), yet additional cases have originated in Florida, Louisiana, California, and the Caribbean.

Roof rat control methods are the same or similar to those used for Norway rats (e.g., toxicants, traps, barriers, deterrents). However, roof rats have been a particular target of recent efforts, both in the United States and in many other countries, to eradicate them from islands where seabirds or other desirable native species are threatened by rat predation (Howald et al. 2007; Witmer et al. 2007a). In Hawaii, Pitt et al. (2011b) recently developed and tested a nest box for endangered Hawaiian cavity-nesting birds that prevents access by roof rats (Figure 10.3).

Polynesian rats (*Rattus exulans*; Figure 10.4), also known as the Pacific rat, or Kiore in New Zealand, is a small tropical rat native to the Southeast Asia mainland that has spread throughout islands in the Pacific in conjunction with human settlement of the region (Matisoo-Smith and Robins 2004). Although they do not occur on the United States mainland, they are well established on most tropical and subtropical islands (less than about 30° latitude) throughout the Pacific, including the Hawaiian Islands (Roberts 1991). Polynesian rats are the smallest species (110–150 mm adult body length) in the genus *Rattus* and are slender (40–100 g for adults) with relatively small feet. Their pelage is reddish-brown to gray-brown on the dorsal surface and light gray or white on the ventral area. Polynesian rats may breed throughout the year and have up to four litters annually with three to six young in each (Tobin 1994). They are sexually mature by one to two months and may have a life expectancy of around one year. Like many rodent species, they are primarily nocturnal, although when densities are high, such as on some tropical islands, they are diurnal and nocturnal.

Polynesian rats may be common to a wide range of habitats from forests to grasslands, and in agricultural croplands, such as sugarcane (Kami 1966). They are good climbers but poor swimmers, so their dispersal to new islands is generally limited by human movement via ships and cargo (McCartney 1970; Spenneman

FIGURE 10.3 Rat-proof bird nest box designed to protect endangered Hawaiian cavity-nesting birds. (Photo by William Pitt.)

FIGURE 10.4 Adult Polynesian rat (approximately 11 cm body length) that is anesthetized to fit a radio-collar for tracking movement patterns in a montane forest on Oahu, Hawaii. (Photo by Aaron Shiels.)

1997; Matisoo-Smith and Robins 2004). Like the other invasive rodents discussed, Polynesian rats are opportunistic omnivores, and their diets vary greatly by what is available according to season and location so as to exploit locally abundant food sources (Kami 1966; Kepler 1967; Fall et al. 1971; Crook 1973; Tobin and Sugihara 1992; Sugihara 1997; Rufaut and Gibbs 2003). In general, their diet is nearly equally split between plant material and arthropods (Shiels et al. 2013; Shiels and Pitt 2014). Predators of Polynesian rats include mongooses, cats, other larger rodents, and birds (Marshall 1962). In addition, many Polynesian cultures consider this rat to be a valuable food resource, and this species and other rodents may have been introduced into new areas intentionally for food (Spenneman 1997).

Polynesian rats are a significant agricultural pest throughout the Pacific region, as they damage a variety of crops including rice, corn, macadamia nuts, sugarcane, coconut, cacao, pineapple, soybeans, and root crops (Strecker 1962; Kami 1966; Tobin and Sugihara 1992). Previous research documented the extensive effects of rat damage on sugarcane, but sugarcane production has largely been replaced by diversified agriculture in Hawaii (Pitt and Witmer 2007). Rat damage has now shifted to high-value seed crops (corn, soybean), tropical fruits, and native plants. Because Polynesian rats were spread through the western Pacific Basin several thousand years ago, and the eastern Pacific at least 600 to 800 years ago (Wilmshurst et al. 2011), modern population and community-level impacts of this rat on the native flora and fauna are not always apparent (Kepler 1967; Crook 1973; Rufaut and Gibbs 2003; Meyer and Butaud 2009). Furthermore, the more recent introductions of the roof and Norway rats, as well as house mice, have potentially masked some of the negative impacts of Polynesian rats on native ecosystems (Shiels 2010; Shiels et al. 2013). Polynesian rats are effective predators of seabirds, lizards, insects, and sensitive plant species that did not evolve with mammalian predators. Recent eradication efforts of Polynesian rats on islands have revealed the extent of their negative impacts as species recovery has occurred, including invertebrates and vertebrates (Gibbs 2009; Newton et al. 2016).

A variety of methods have been employed to reduce the effects of Polynesian rats on agriculture and natural resources (Jackson 1977). The most successful attempts have integrated rodenticides, alteration of cultural practices, and trapping (Sugihara 1977). Rodenticides have been effectively used to reduce agricultural damage, protect forest birds, and protect seabird colonies. Previous attempts to control rat damage using biological methods (e.g., predator introductions) have been unsuccessful and deleterious for other species. The most frequently cited failure is the introduction of the mongoose (*Herpestes auropunctatus*) to Hawaii in 1883, which has had cascading impacts on ecosystem function (Pitt and Witmer 2007).

Gambian giant pouched rats (*Cricetomys gambianus*; Figure 10.5), referred to hereafter as the Gambian rat, are native to a large area of central and southern Africa. They had become popular in the pet industry and likely were released by a pet breeder and subsequently became established on Grassy Key in the Florida Keys in 1999 (Engeman et al. 2006; Perry et al. 2006). Despite a prolonged eradication effort, a free-ranging and breeding population remained on the island (Engeman et al. 2006, 2007; Witmer and Hall 2011). There is a concern that if this species reaches the mainland, there could be damage to the Florida fruit industry because Gambian rats are known to damage numerous types of agricultural crops in Africa (Fiedler 1994). Imported Gambian rats also may serve as reservoirs of monkey pox and other diseases. An outbreak of monkeypox occurred in the Midwestern United States in 2003 as a result of infected Gambian rats imported from Africa for the pet industry (Enserink 2003). A climate-habitat modeling study suggested that their new range in North America could expand substantially if they were to become established on the United States mainland (Peterson et al. 2006).

FIGURE 10.5 Gambian giant pouched rat captured in a racoon-sized cage trap on Grassy Key, Florida. (Photo by Gary Witmer.)

Gambian rat pelage is gray-brown in color, and they can reach a considerable size: about 2.8 kg in weight and about 1 m in length, body and tail combined (Kingdon 1974). Females produce four young per litter and can bear eight or more litters per year (Ajayi 1975). Because of their reproductive potential and large size, Gambian rats have been raised in captivity as a source of protein in Africa (Ajayi 1975). Since free-ranging Gambian rats are a relatively recent addition to the rodent fauna of North America, relatively little is known about their biology, habitat use, impacts, and interactions with native species or about the most effective means to capture or control these rodents. Hence, current efforts are concentrating on use of traditional live trap capture methods (Figure 10.5) and rodenticides in bait stations (Engeman et al. 2007; Witmer and Hall 2011). Eradicating Gambian rats from Grassy Key has proven problematic because of the large number of private properties on the island, some of whose owners will not allow government employees or the use of rodenticides on their property (Witmer and Hall 2011). Therefore, it will be important to develop additional tools to manage or eradicate this species and other rodent invaders in the United States (Witmer et al. 2010a,b; Witmer and Hall 2011).

House mice (*Mus musculus* and *M. domesticus*; Figure 10.6) are native to southern Europe, northern Africa, and Asia (Long 2003). They now occur worldwide and are probably the most numerous and widespread mammalian species in the world next to humans (Witmer and Jojola 2006). While house mice are thought to have first originated in the grasslands of Central Asia, they have been transported by humans to most parts of the world, largely as stowaways on ships and in cargo. House mice have remarkable abilities that have allowed them to be highly successful in many habitats around the world; chief among these are their reproductive potential and their adaptability in different environments (Timm 1994b; Witmer and Jojola 2006).

House mice are small, slender rodents with a pelage that is grayish-brown on the dorsal surface and gray to buff on the ventral area. This small (maximum mass in United States is about 20 g for adults) and highly prolific animal is a continuous breeder in many situations; a female can produce five to 10 litters—each with five to six young—per year (Timm 1994b). The young mature within about three weeks and soon become reproductively active. House mice are short-lived (generally less than one year) and have high population turnover. In one study, 20 mice placed in an outdoor enclosure with abundant food, water, and cover became a population of 2000 in eight months (Corrigan 2001).

House mice cause many types of damage (Timm 1994b; Witmer and Jojola 2006). A major concern is their role in the consumption and contamination of stored foods; it has been estimated that substantial amounts of stored foods are lost each year in this manner. Mice may damage many types of crops in the field, especially corn, cereal grains, and legumes. Mice also consume and contaminate large amounts of livestock feed at animal production facilities. While mice generally live in close proximity to humans (Corrigan 2001), sometimes remote populations occur such as in many natural areas in Hawaii from sea level to nearly 4000 m elevation (Shiels 2010). Australia has mouse "plagues" periodically, resulting in enormous losses to stored crops and crops in fields (Brown et al. 2004). In buildings, a mouse infestation can be a considerable nuisance because of the noise, odors, and droppings. More

FIGURE 10.6 House mice have amazing abilities which allow them to access almost any available area or resource. (Photo source unknown.)

importantly, they damage insulation and wiring (Hygnstrom 1995). House fires have been caused by mice gnawing electrical wires; likewise, communication systems have been shut down for periods of time, resulting in economic losses (Timm 1994b). Additionally, house mice are susceptible to a large number of disease agents and endoparasites. Consequently, they serve as reservoirs and vectors of disease transmission to humans, pets, and livestock (Gratz 1994). Important among these diseases are leptospirosis, plague, salmonella, lymphocytic choriomeningitis, and toxoplasmosis.

When introduced to islands, house mice can cause significant damage to natural resources, including both flora and fauna. For example, on Gough Island in the South Atlantic, house mice fed on nestling albatross chicks (Cuthbert and Hilton 2004). Additionally, Witmer et al. (2012b) documented seedling damage by house mice in a pen study. House mice are omnivores, yet their diet is largely dominated by insects, some of which are likely plant pollinators (Shiels et al. 2013; Shiels and Pitt 2014). House mice are subordinate to introduced rats, so the impacts of mice may go unnoticed when rats are also present on the island (Angel et al. 2009). This phenomenon was demonstrated by the large increase in mice abundance on Buck Island, U.S. Virgin Islands, after invasive roof rats were eradicated (Witmer et al. 2007a). In very dry habitats on islands, house mice may numerically dominate over introduced rats.

A large number of methods and materials have been developed to help solve house mouse problems. In general, the use of multiple approaches and materials—integrated pest management (IPM)—is more likely to reduce a mouse problem to a tolerable level (Witmer 2007). For example, sanitation and blocking of small access openings can be combined with some use of traps (kill traps and/or live traps) and/or toxicants. The tools available and their proper use have been extensively reviewed (Brooks 1973; Prakash 1988; Timm 1994b; Corrigan 2001).

INVASIVE RODENT MANAGEMENT TOOLS AND RESEARCH NEEDS

Many methods and tools have been developed and used to control rodent populations or to reduce the damage they cause (Table 10.1). The methods that are commonly used vary greatly from region to region around the world, as well as between developed and undeveloped countries. Methods used also vary with regard to the type of management. When long-term population suppression is the management goal (such as in agricultural and urban/suburban settings), a variety of approaches are used, generally through an IPM strategy (Witmer 2007). While traps and rodenticides are the mainstays of rodent population management, IPM also employs habitat management, exclusion, and sanitation (Hygnstrom et al. 1994). On the other hand, if eradication of the invasive rodent species is the management goal, rodenticides are heavily relied upon, although traps may be used to some extent in combination with rodenticides. Some of the methods are highly regulated, and regulations vary across political jurisdictions. The many methods used to manage rodent populations and damage have been described at length by Prakash (1988), Corrigan (2001), Buckle and Smith (2015), Hygnstrom et al. (1994), and Caughley et al. (1998). One novel technique that was recently tested and may deserve further research was the use of live laboratory rats as lures to trap invasive wild Norway rats; the live rats, regardless of gender, were more efficient than food baits for catching invasive rats (Shapira et al. 2013b). Similar testing using laboratory mice to attract wild house mice has also been investigated (Shapira et al. 2013a). In this chapter, we will only address in detail traps and rodenticides as invasive rodent population management techniques.

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

TABLE 10.1
Methods and Techniques for Rodent Control That Have Been Suggested, Tested, or Used to Reduce Rodent Populations and Damage around the World

Physical	Chemical	Biological	Other
Rodent proof construction	Baits/baiting systems	Virally vectored 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		Endophytic grasses	
Digging		Unpalatable plants	
Dogs together with flooding or digging			

Source: Modified from Witmer, G. and Singleton, G., *Agricultural Production*, New York, New York, Nova Science Publishers, Inc., 1–38, 2010.

the leg-hold trap which, when tripped by the rodents paw, springs the jaws of the trap to close tightly around the leg and hold the animal until the trapper arrives. Leg-hold traps are generally only used for larger rodent species such as nutria, muskrats (*Ondatra zibethicus*), and beaver (*Castor canadensis*). Invasive rodents captured in live traps can be used in research or euthanized. An advantage of live traps is that nontarget animals captured can often be released unharmed.

Kill traps cause the rapid death of the rodent by body constriction when the animal trips the trap's trigger mechanism. The most common type of rodent kill trap is the snap trap. Alternatively, Conibear kill traps can be used for larger rodent species. Automatically self-resetting rat kill traps have been recently developed in New Zealand by Goodnature® (e.g., Peters et al. 2014). Known as the Goodnature® A24 rat traps (or A24s), they can fire up to 24 times before the CO_2 cartridge must be replaced. The A24 traps are relatively expensive compared to nonautomatic traps, and currently cost about $112 per unit. Although A24 traps have been used widely over the past few years, including in Hawaii, California, and Puerto Rico, mixed results have been observed in their reliability and effectiveness. In fact, the New Zealand government spent NZ$4 million to test the Goodnature® traps, and the A24s were determined to be ineffective for rat control due to mechanical failure and bait palatability issues (Gillies et al. 2012). Improved reliability and effectiveness of such automated traps as the Goodnature® A24s will certainly help expand the number of options to efficiently suppress invasive rodents (Campbell et al. 2015).

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, and use of the proper type of trap for the situation, proper placement, and appropriate bait is important to achieve a high level of trap success (i.e., a high capture rate). 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 too large, at which point extensive damage to resources cannot be avoided (Witmer 2005). Rodent population monitoring before and during rodent suppression is also important to justify the use and effectiveness of the rodent control technique.

Rodenticides are widely used in the United States as well other parts of the world. Because of the risk of harm to people, pets, and livestock, rodenticides are carefully regulated by the United States Environmental Protection Agency (EPA), as well as by state agencies. There are many types of rodenticides, and these vary by active ingredient as well as formulation (Table 10.2). These materials vary widely in their mode of action and in toxicity. The types and uses of rodenticides in the United States were reviewed by Witmer and Eisemann (2007), and their specific use for conservation purposes (i.e., the control or eradication of invasive rodents) was reviewed by Witmer et al. (2007b).

Proper training and careful use are required to safely use rodenticides so that they are effective in reducing rodent populations while minimizing the hazard to nontarget animals. An EPA-approved product label provides considerable information on the product and its use, including: the registrant and EPA registration number(s), active ingredient and concentration, target species and settings in which it can be used, directions for use, storage and disposal requirements, precautionary statements, safety and environmental hazards, and threatened and endangered species considerations (Figure 10.7).

Both primary (direct consumption) and secondary hazards (consuming a poisoned rodent or poisoned nontarget animal) can occur to nontarget animals when rodenticides are used (Masuda and Jamieson 2013; Pitt et al. 2015). Rodenticides such as brodifacoum (a second generation anticoagulant) are highly toxic, but also result in persistent residues in body tissues of animals that consume lethal or sublethal doses or consume rodents that have been poisoned (Witmer and Eisemann 2007). There are growing concerns about persistence, chronic use, and the subsequent chronic secondary effects of these residues in nontarget and predatory animals (Thomas et al. 2011; Masuda and Jamieson 2013; Pitt et al. 2015; Elliott et al. 2016). The main safeguard for the safe use of rodenticides in the United States is carefully following the EPA label instructions for the product. Other considerations include: the product used; when, where, and how it is applied; cleaning up spills promptly; and not using rodenticides where highly valued or protected wildlife occur (determined by scouting and surveying the area before use).

TABLE 10.2
The Main Rodenticides Used in the United States by Category and Percent Active Ingredient

Acute rodenticides
- Cholecalciferol (0.075%)
- Strychnine (0.5%)
- Zinc phosphide (2%)
- Bromethalin (0.01%)

Fumigants
- Aluminum phosphide (56%)
- Magnesium phosphide (56%)
- Acrolein (95%)
- Gas cartridges (variable)

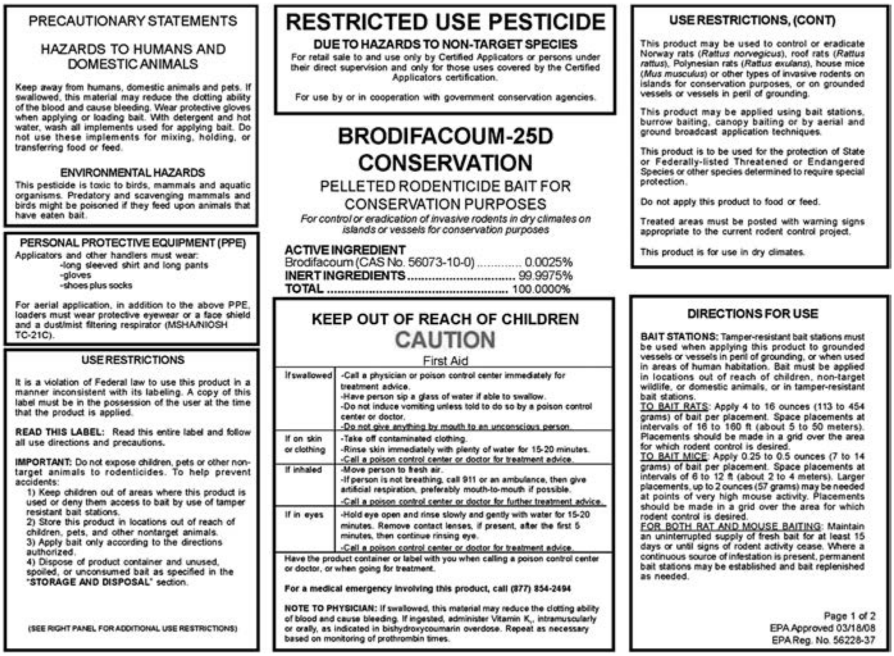
First-Generation Anticoagulants
- Chlorophacinone (0.005%)
- Diphacinone (0.005%)
- Warfarin (0.025%)
- Pindone (0.025%)

Second-Generation Anticoagulants
- Bromadiolone (0.005%)
- Brodifacoum (0.005%)
- Difethialone (0.0025%)

Source: Witmer, G. and Eisemann, J. D., *Proceedings of the 12th Wildlife Damage Management Conference*, Corpus Christi, Texas, 12th Wildlife Damage Management Conference, 114–118, 2007.

Additional research is needed to improve existing methods and to develop new methods for invasive rodent detection and control, including both lethal and nonlethal means of resolving rodent damage situations (Witmer et al. 1995; Eason et al. 2010; Witmer and Singleton 2010; Blackie et al. 2014; Campbell et al. 2015). Future research should include, but not be limited to, developing new rodenticides, more effective repellents and barriers, improved biological control, fertility control, and habitat manipulation. Some exciting areas of new research on invasive rodent control methods include:

- Resetting, long-life toxin delivery systems
- Increasing knowledge of pest behavior
- New active ingredient toxicants
- Long-life bait coatings
- Crab deterrents for bait
- Transgenic rodents (genetic manipulation)
- More stakeholder engagement and increased understanding of social processes



PRECAUTIONARY STATEMENTS

HAZARDS TO HUMANS AND DOMESTIC ANIMALS

Keep away from humans, domestic animals and pets. If swallowed, this material may reduce the clotting ability of the blood and cause bleeding. Wear protective gloves when applying or loading bait. With detergent and hot water, wash all implements used for applying bait. Do not use these implements for mixing, holding, or transferring food or feed.

ENVIRONMENTAL HAZARDS

This pesticide is toxic to birds, mammals and aquatic organisms. Predatory and scavenging mammals and birds might be poisoned if they feed upon animals that have eaten bait.

PERSONAL PROTECTIVE EQUIPMENT (PPE)

Applicators and other handlers must wear:
-long sleeved shirt and long pants
-gloves
-shoes plus socks

For aerial application, in addition to the above PPE, loaders must wear protective eyewear or a face shield and a dust/mist filtering respirator (MSHA/NIOSH TC-21C).

USE RESTRICTIONS

It is a violation of Federal law to use this product in a manner inconsistent with its labeling. A copy of this label must be in the possession of the user at the time that the product is applied.

READ THIS LABEL: Read this entire label and follow all use directions and precautions.

IMPORTANT: Do not expose children, pets or other non-target animals to rodenticides. To help prevent accidents:
1) Keep children out of areas where this product is used or deny them access to bait by use of tamper resistant bait stations.
2) Store this product in locations out of reach of children, pets, and other nontarget animals.
3) Apply bait only according to the directions authorized.
4) Dispose of product container and unused, spoiled, or unconsumed bait as specified in the "**STORAGE AND DISPOSAL**" section.

(SEE RIGHT PANEL FOR ADDITIONAL USE RESTRICTIONS)

RESTRICTED USE PESTICIDE

DUE TO HAZARDS TO NON-TARGET SPECIES

For retail sale to and use only by Certified Applicators or persons under their direct supervision and only for those uses covered by the Certified Applicators certification.

For use by or in cooperation with government conservation agencies.

BRODIFACOUM-25D CONSERVATION

PELLETED RODENTICIDE BAIT FOR CONSERVATION PURPOSES

For control or eradication of invasive rodents in dry climates on islands or vessels for conservation purposes

ACTIVE INGREDIENT
Brodifacoum (CAS No. 56073-10-0) 0.0025%
INERT INGREDIENTS 99.9975%
TOTAL 100.0000%

KEEP OUT OF REACH OF CHILDREN

CAUTION

First Aid

If swallowed	-Call a physician or poison control center immediately for treatment advice. -Have person sip a glass of water if able to swallow. -Do not induce vomiting unless told to do so by a poison control center or doctor. -Do not give anything by mouth to an unconscious person.
If on skin or clothing	-Take off contaminated clothing. -Rinse skin immediately with plenty of water for 15-20 minutes. -Call a poison control center or doctor for treatment advice.
If inhaled	-Move person to fresh air. -If person is not breathing, call 911 or an ambulance, then give artificial respiration, preferably mouth-to-mouth if possible. -Call a poison control center or doctor for further treatment advice.
If in eyes	-Hold eye open and rinse slowly and gently with water for 15-20 minutes. Remove contact lenses, if present, after the first 5 minutes, then continue rinsing eye. -Call a poison control center or doctor for treatment advice.

Have the product container or label with you when calling a poison control center or doctor, or when going for treatment.

For a medical emergency involving this product, call (877) 854-2494

NOTE TO PHYSICIAN: If swallowed, this material may reduce the clotting ability of blood and cause bleeding. If ingested, administer Vitamin K_1, intramuscularly or orally, as indicated in bishydroxycoumarin overdose. Repeat as necessary based on monitoring of prothrombin times.

USE RESTRICTIONS, (CONT)

This product may be used to control or eradicate Norway rats (*Rattus norvegicus*), roof rats (*Rattus rattus*), Polynesian rats (*Rattus exulans*), house mice (*Mus musculus*) or other types of invasive rodents on islands for conservation purposes, or on grounded vessels or vessels in peril of grounding.

This product may be applied using bait stations, burrow baiting, canopy baiting or by aerial and ground broadcast application techniques.

This product is to be used for the protection of State or Federally-listed Threatened or Endangered Species or other species determined to require special protection.

Do not apply this product to food or feed.

Treated areas must be posted with warning signs appropriate to the current rodent control project.

This product is for use in dry climates.

DIRECTIONS FOR USE

BAIT STATIONS: Tamper-resistant bait stations must be used when applying this product to grounded vessels or vessels in peril of grounding, or when used in areas of human habitation. Bait must be applied in locations out of reach of children, non-target wildlife, or domestic animals, or in tamper-resistant bait stations.
TO BAIT RATS: Apply 4 to 16 ounces (113 to 454 grams) of bait per placement. Space placements at intervals of 16 to 160 ft (about 5 to 50 meters). Placements should be made in a grid over the area for which rodent control is desired.
TO BAIT MICE: Apply 0.25 to 0.5 ounces (7 to 14 grams) of bait per placement. Space placements at intervals of 6 to 12 ft (about 2 to 4 meters). Larger placements, up to 2 ounces (57 grams) may be needed at points of very high mouse activity. Placements should be made in a grid over the area for which rodent control is desired.
FOR BOTH RAT AND MOUSE BAITING: Maintain an uninterrupted supply of fresh bait for at least 15 days or until signs of rodent activity cease. Where a continuous source of infestation is present, permanent bait stations may be established and bait replenished as needed.

Page 1 of 2
EPA Approved 03/18/08
EPA Reg. No. 56228-37

FIGURE 10.7 EPA-approved label for a rodenticide designed for invasive rodent eradication on islands.

We believe there is a need to identify effective, commercially available rodenticide formulations for the various invasive rodents in each region of the country, as Pitt et al. (2011c) have done for rats and mice in Hawaii, and Witmer and Moulton (2014) did for Norway rats and mice in the North American mainland. Another important research need is greater evaluation of the effectiveness of combinations of techniques, given that combinations could potentially be much more effective in the reduction of damage and may be more acceptable to the public.

INVASIVE RODENT ERADICATION

Since the early 1990s, federal and state agencies, along with conservation organizations, have been eradicating rodents from various islands in the United States, primarily for conservation purposes. To date, 644 successful eradications of rats on islands worldwide have been reported (DIISE Partners 2016), and the great majority of these have involved roof, Norway, and Polynesian rats. In general, successful rat eradications from tropical islands (89%) have been somewhat lower than successes in temperate islands (96%; Keitt et al. 2015). Some suggestions on why the lower success rate on tropical islands include (1) increased crab and insect densities resulting in competition for bait, (2) year-round and unpredictable breeding by rats, and (3) increased or unpredictable availability of alternative, natural foods (Keitt et al. 2015; Holmes et al. 2015b). Witmer et al. (2011) documented the attempted eradications of introduced rodents in the United States and its territories. Of about 40 island eradication attempts, 22 (55%) or more appear to have succeeded. For several islands, however, it is too early to determine if the attempted eradication has been successful. Additionally, experimental rat eradication trials on 12 small islands in The Bay of Islands, Adak, Alaska, failed or rapid reinvasion occurred, and those perhaps should not be included in the list of more concerted eradication efforts as eradication methods were being investigated (Witmer et al. 2011). In some cases, what appeared to be failed eradications may have resulted from rapid reinvasion by rats from nearby islands, suggesting the need to eradicate rats from groups of islands as an eradication unit (Savidge et al. 2012). Genetic analyses of rats before and after eradications are often necessary in helping sort out the issue of reinvasion versus failed eradication (Keitt et al. 2015). Numerous islandwide rodent eradications are underway or being planned. Most rodent eradications around the world have used the second-generation anticoagulant brodifacoum (Howald et al. 2007). In the United States, however, most eradications have used the first-generation anticoagulant diphacinone (Witmer et al. 2011). Early rodent eradications used hand-broadcast and bait stations of rodenticides, but in recent years, aerial broadcast via helicopter has become common. Aerial broadcast of rodenticide bait allows rodent eradications on much larger and more rugged islands, such as Rat Island, Alaska (2700 ha; Witmer et al. 2011). There are large cost differences between aerial and ground applications of rodenticides for island eradications; most aerial-based operations cost between $1 and $3 million (Holmes et al. 2015a), whereas ground-based operations are mere thousands, and the most expensive listed in the Holmes et al. (2015a) review was about $300,000 (Buck Island; Witmer et al. 2007a). Aerial application, however, has allowed very large islands to be treated, islands so large they could not be treated by hand broadcast (e.g., Rat Island in the Aleutian Islands) where rats were successfully eradicted, is 2780 ha). In the United States and most other countries in the world, aerial application of rodenticide is typically used for invasive rodent eradication purposes rather than invasive rodent population suppression; however, in New Zealand, aerial broadcast of toxic baits (e.g., 1080) has been used for decades to suppress, rather than eradicate, invasive possums (*Trichosurus vulpecula)* and rats (*Rattus* spp.; Morgan et al. 2015). Currently, the U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) has two rodenticides registered with the EPA for island conservation purposes: one formulation of diphacinone pellets and two formulations of brodifacoum pellets (Witmer et al. 2007b; Figure 10.7).

When using rodenticides, a variety of considerations and mitigation measures are employed to avoid, reduce, or minimize nontarget hazards and environmental impacts; some include the rodenticide type, amount (Pott et al. 2015), formulation, method and timing of baiting (Keitt et al. 2015), captive holding and later release of some nontarget wildlife species until after the baiting operation, removal of rodent carcasses to prevent secondary poisoning, and avoidance of bait placement in aquatic systems (Witmer et al. 2007b). In general, impacts to nontarget species during invasive rodent eradications should be considered in terms of population-level effects, rather than the effects to individuals, and the benefits should outweigh the costs of the project implementation. While there will probably always be some losses of nontarget animals, proper precautions should minimize such risk and allow for the rapid recovery of affected populations (Howald et al. 2005). For example, Croll et al. (2016) determined that despite initial nontarget mortalities (including bald eagle reduction from 24 individuals to two individuals), within five years posteradication of rats, the bald eagles, terrestrial birds, and shorebirds had colonized, recolonized, or otherwise increased in abundance to levels near to or above those of pre-eradication on an Aleutian Island in Alaska. Those involved with successful invasive rodent eradications on islands are often surprised at how rapidly the island's flora and fauna recover or change after rodents are removed (Witmer et al. 2007a; Croll et al. 2016).

Planning and conducting a successful invasive rodent eradication from an island poses many challenges and should not be undertaken without a thorough commitment and adequate resources. The basic tenets of a successful eradication are: all individuals (i.e., target rodent species) must be put at risk; rodents must be removed faster than they can reproduce; and the risk of immigration must be zero (Parkes and Murphy 2003). An eradication attempt that is 99% successful can ultimately result in 100% failure due to the high reproductive potential of the remaining rodent population. Because of the large commitment of resources and usually public funds in eradication efforts, the potential for failure should be minimized, and there have been a number of factors that have been identified that commonly influence whether a rodent eradication attempt is successful (e.g., see Keitt et al. 2015; Holmes et al. 2015b). Planning and implementation components include:

- Preliminary monitoring and research
- Feasibility of eradication
- Regulatory compliance
- Public information and communications media
- Public support
- Technical assistance and operations
- Planning
- Logistics
- Procurement of equipment and other services
- Monitoring and research
- Staff recruitment and training
- Implementation
- Contingency planning
- Follow-up monitoring
- Implementation of a biosecurity plan

REMAINING AND FUTURE CHALLENGES

A number of challenges remain with invasive rodent management and eradication in the United States. Some of the challenges faced include public and agency concerns about animal welfare issues, uncertainties with pesticide use, the necessary investments to achieve conservation goals, the use of certain toxicants and traps, land access (especially to private lands), public attitudes, resource availability, and detection and monitoring difficulties (Witmer and Hall 2011; Witmer et al. 2011).

Nonetheless, we will hopefully continue to relieve the burdens on insular and mainland ecosystems caused by rodent introductions. This is also essential to ensure adequate food resources for humans and livestock worldwide. The flora and fauna of islands generally respond rapidly, and conservation goals are achieved after invasive rodents are removed and often without much additional input by people (e.g., Witmer et al. 2007a; Witmer et al. 2011; Croll et al. 2016; Newton et al. 2016). Endemic, threatened, or endangered species can be, and have been, reintroduced after successful rodent eradications. For example, the endangered St. Croix ground lizard (*Ameiva polops*) was recently reintroduced to Buck Island in the U.S. Virgin Islands after the successful eradication of roof rats (Witmer et al. 2007a). The recent eradication of Polynesian rats and house mice from Cocos Island (a small island off of Guam) set the stage for the reintroduction of the endangered Guam rail, *Gallirallus owstoni* (Lujan et al. 2010).

CONCLUSIONS

Invasive rodents will continue to pose challenges to land and resource managers, commodity producers, and homeowners. Although preventing rodent invasion beyond their native range is the most idealized way of preventing their negative impacts as an invasive species, it is not always possible, and the rodents described in this chapter have clearly invaded much of the United States. Many tools are available to reduce rodent populations and associated damage, and these tools should be used in a well thought out IPM approach. Rodenticides will continue to be an important tool against 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 scrutinize certain tools, such as toxicants. Hence, public outreach and education will be important to ensure continued availability of adequate tools, such as rodenticides, until such time as new and emerging technologies can be developed, tested, registered and regulated, and adopted widely (Witmer et al. 2009; Eason et al. 2010; Witmer and Singleton 2010; Blackie et al. 2014; Campbell et al. 2015). Continued technology development and transfer to agencies, companies, and the public are essential to improve the effectiveness and safety of rodenticides and other methods used to control or eradicate invasive rodents. With proper planning, nontarget losses from invasive rodent suppression or eradication will be minimal, and these nontarget populations, along with other island and mainland resources, will be ensured and often recover quickly after the invasive rodents have been removed.

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