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PEST CONTROL: RODENTS

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Summary

Rodents are an important and ubiquitous group of mammals that occur as indigenous or introduced species throughout the world. The populations of a relatively few species that live in close association with humans sometimes cause economic damage or become threats to the health of humans or domestic animals. When rodent control efforts are contemplated, the type of problem and the objectives of these efforts should be carefully defined. Successful management of rodent problems depends upon correct identification of the rodent species involved and on obtaining information on the biology, ecology, and behavior of the species in the ecological setting where the problem occurs. Analyzing the economic costs of potential damage or assessing the risks of failure or inaction can assist in the selection of appropriate combinations of control methods to employ. Progress in rodent control programs should be monitored regularly and success should be measured against the achievement of appropriate objectives (for example, prevention of crop damage or prevention of rodent infestations in warehouses or feed mills), not by counting the numbers of rodents killed or the amount of poison bait applied. No single method of rodent control will be predictably effective in all situations; IPM programs that apply several methods appropriate to the species and the environment where a problem occurs offer the best prospects for long-term success.

1. Introduction

Rodents are the largest, and one of the most interesting, groups of mammals. They are important components of virtually all of the earth's terrestrial ecosystems and are important herbivores that aerate the soil by burrowing activities and assist plant propagation by consuming and disseminating seeds. They are often the most important food base for many predatory mammals and birds, acting to sustain populations of these species. However, rodents also are important vectors or reservoirs of numerous diseases that infect humans, domestic animals, and other wildlife species. They are significant economic pests that devastate crops, gardens, orchards, or landscape plantings, and damage commercial forest plantations or impede reforestation efforts. Rodents burrow through dams and irrigation structures, gnaw through communications cables

and damage electronics, and consume or contaminate stored food and other commodities. Rodents sometimes prey on the eggs or young of wild birds and compete with native wildlife species for food or habitat, and thus have become important concerns in the management and recovery of threatened or endangered species, particularly in island environments.

Rodent control describes the processes that people use to alleviate rodent damage, to prevent the spread of rodent-borne diseases, to reduce problem rodent populations, or to eliminate rodent infestations. Depending on the species of rodents involved, the kinds of environments where problems occur, the nature of the problem, and the value of anticipated damage, a variety of methods is available for controlling damage or reducing rodent populations. Usually, several methods need to be used systematically to achieve lasting results. The process of selecting, applying, and evaluating the results of such combinations of control methods in relation to the ecological and economic aspects of specific damage problems is called integrated pest management (IPM) or ecologically-based pest management.

2. Characteristics of Rodents

Because of the diverse characteristics of rodent species for which rodent control may be a concern, only a very general discussion is possible. The biology, ecology, and behavior of each species or even of the same species occurring in different environments must be examined carefully to develop successful rodent control programs. What might work effectively for rodent control in a grain warehouse or urban sewer system would have little applicability or would be impractical in an Asian rice field. However, the kinds of information needed and the principles used to develop an IPM program are the same.

There are more than 2000 recognized species of rodents (Wilson and Reeder 1993), many of which are described and pictured in Nowak (1999). A relative few of these species, perhaps less than 250 worldwide, interact sufficiently with humans to cause economic, conservation, or health concerns sufficient to warrant rodent control efforts. Biologists often rename or combine different groups of rodents to better reflect relationships as new scientific information becomes available. Whenever possible, current scientific names for rodents (Wilson and Reeder 1993) have been used when citing information from older literature.

Many readers are most familiar with "rats and mice" as the animals commonly associated with rodent control. The Norway rat (*Rattus norvegicus*), also known locally as the brown rat, wharf rat, sewer rat, or barn rat, has a nearly worldwide distribution and is almost always found living in close association with humans. The roof rat or black rat (*Rattus rattus*) and the house mouse (*Mus musculus*) are also widely distributed and, together with the Norway rat, are known as commensal rodents because of their generally close association with human habitation. Rodents range in size from the South American capybara (*Hydrochaeris hydrochaeris*), weighing more than 50 kg, to the harvest mouse (*Micromys minutus*) of Eurasia, weighing 5 to 7g. Most rodent species have thick fur, although great variations in pelage occur. The naked mole rats (*Heterocephalus glaber*) of Africa have only bare skin, while porcupine species, such as (*Erithizon dorsatum*) of North America, have highly modified coats containing spines or quills that help provide protection from predators. Hearing, smell, taste and touch are well-developed senses in rodents, but as with many mammals, particularly the nocturnal species, their vision is relatively poor and they apparently do not distinguish colors. Rodents detect sound at frequencies substantially higher than humans; some species may use ultrasound as a means of

communication (Blanchard et al. 1991). Most rodents have long whiskers or vibrissae around their muzzles that are highly sensitive and may be used in following runways or burrows. Many rodent species are excellent climbers, using their long tails for balance. Most rodents readily swim; some, like beavers (*Castor canadensis*), nutria (*Myocastor coypus*), muskrats (*Ondatra zibethicus*), and web-footed rats (*Holochilus sciureus*), have modified appendages such as flattened tails or webbed feet that facilitate their use of freshwater aquatic habitats.

Most species of rodents are born naked and helpless, but mature rapidly. Norway rats (*Rattus norvegicus*), for example, have a gestation period of about 3 weeks, become independent of the mother at about 3 weeks after birth, and can breed for the first time within another 3 weeks. Rodents are omnivorous, exhibiting choices and preferences in their diet, but often selecting the most abundant, palatable foods available. They readily learn to reject or avoid unpalatable foods or those containing toxins, which presents a problem for the development of bait materials for effective delivery of rodenticides. The front teeth, or incisors, of rodents grow continuously and are also worn continuously by gnawing on objects or food. Because of the large space or diastema behind their incisors, rodents can use these front teeth to investigate or nibble unfamiliar materials without actually taking them inside their mouths.

3. Rodent Populations

Because of the high reproductive capacity of rodents, their populations can grow rapidly to utilize available habitat and food. In stable environments rodents self-regulate their populations. When a population reaches the carrying capacity of an environment, reproduction declines and excess animals die (usually from disease, parasites, or predation) or emigrate to new areas. Yet rodents survive very adverse conditions—even nuclear explosions!—by living in underground burrows (Jackson 1969) and rebuilding their populations when conditions again become favorable. Habitat disruption or climatic changes that lead to increases in food and harborage sometimes give rise to population outbreaks or irruptions of some rodent species, resulting in extremely high populations that can inflict severe damage on crops (Fiedler and Fall 1994). Libay and Fall (1976) observed densities of 1 adult rat per square meter (10 000 rats per hectare!) in a breeding population of *Rattus tanezumi* in a large marsh area in the Philippines adjacent to a ricefield basin.

Rattus argentiventer in Southeast Asia, the multimammate rats (*Mastomys natalensis*) in Africa, *Mus musculus* in Australia and Hawaii, the jirds, *Meriones hurrianae* and *Meriones shawi*, in South Asia and North Africa, the Microtines (voles and lemmings) in Eurasia and North America, and cotton rats (*Sigmodon hispidus*) in southern USA and Central America all undergo periodic population irruptions. Scientists are continuing to study ways to predict such rodent outbreaks and prevent their occurrence (or at least reduce the associated damage). Surveillance of rodent populations, particularly in agricultural areas where outbreak species occur, is often an important component of rodent control.

Rodent population irruptions may result in damage that is highly visible and often spectacular, devastating crop fields over wide areas. However, chronic damage and the risks of rodent-borne disease are often a greater concern from the viewpoints of economics and public health and can occur when rodent populations are relatively low—or in cases of diseases carried by rodent feces or urine, when rodents are absent. There are few places in the world where rodents are not closely associated with human enterprise. The potential for chronic losses of crops, losses and

contamination of stored products, and transmission of rodent-borne diseases requires careful monitoring to determine if rodent control programs are needed or appropriate.

4. Types of Rodent Problems

The diversity of problems caused by rodents throughout the world is so great that only a few examples of some general categories of problems can be discussed. We provide a list of additional readings at the end of this chapter for readers who wish to obtain more information about rodent pest species and the different types of problems they cause in different areas of the world.

4.1. Grain Crops

Rat damage to ripening rice crops in Asia, Africa, and Latin America can be an extremely serious agricultural problem, although economic losses are often difficult to estimate because of complex patterns of growth and recovery of plants related to the developmental stage when damage occurs (Fall 1977, Fall 1980, Buckle 1994). Rats can completely consume fields of growing rice and sometimes prevent planting where crops could otherwise be grown (Wood 1994). Wheat, sorghum, maize and other grain crops are also damaged extensively by various rodent species in different parts of the world, and patterns of damage vary considerably depending on the behavior of the species involved. For example, *Bandicota bengalensis* in southern Asia cuts mature wheat and rice in large patches and establishes extensive underground food caches (Poche et al. 1982); *Rattus tanezumi* and *Rattus argentiventer* in the Philippines and other areas of Southeast Asia feed upon all stages of growing rice (Fall, 1977), while *Sigmodon hispidus* in Central America avoids wet areas in rice fields and causes damage after water is removed to dry the crop before harvest.

4.2. Sugarcane

Rodents cause extensive damage to ripening sugarcane wherever it is grown, from Asia to Africa, Latin America, the Pacific region, and Australia (Fiedler et al. 1987, Fall 1980, Tobin et al. 1990). Rats gnaw on the internodes of growing stalks, thereby killing stalks, diminishing yields, or allowing infection by bacteria or fungus, which reduces cane quality and sugar yield. Losses are difficult to quantify but can be substantial (Redhead 1980, Hampson 1984, Haque et al. 1985, Rampaud 1993, Engeman et al. 1998b). The major depredating species vary from area to area and include: *Rattus rattus, Rattus norvegicus,* and *Rattus exulans* in Hawaii*; Holochilus scuireus, Sigmodon hispidus, Oryzomys palustris, Mus musculus,* and *Rattus rattus* in North and South America*; Rattus tanezumi* in Southeast Asia*; Millardia meltada, Bandicota bengalensis,* and *Bandicota indica* on the Indian subcontinent*; Rattus losea* and *Bandicota bengalensis* in China; *Mus caroli and Apodemus agrarius* in Taiwan; *Rattus sordidus and Melomys burtoni* in Australia; and *Rattus rattus, Arvicanthis niloticus,* and *Thryonomys swinderianus* in Africa (Taylor 1984, Fiedler 1988, Prakash and Mathur 1988, Wood 1994).

4.3. Orchard and Plantation Crops

Voles (*Microtus sp*.) cause extensive damage in fruit orchards in USA and Europe (Tobin and Richmond 1993, Guedon and Combes 1990). Populations of these rodents typically irrupt periodically and, when preferred vegetation is scarce, particularly in winter, gnaw the roots and trunks of trees for the underlying phloem and cambium tissue. The resulting damage interferes

with transport of nutrients between the roots and aerial portions of the tree and increases the chance of infection by root pathogens. The resulting damage kills trees, reduces fruit production, and increases the time for new plantings to come into production. Coconuts are grown commercially in many tropical areas and are subject to damage by several rodent species, particularly *Rattus rattus* and *Rattus tanezumi*. These rodents climb palms of all ages, primarily to feed on developing nuts, which then fall prematurely to the ground (Fiedler et al. 1982, Wood 1994). The proportion of nuts that drop prematurely due to rat damage can be quite high. Impacts on yield may not be proportional to the number of developing coconuts that fall to the ground (Williams 1974, Reidinger and Libay 1981, Fiedler et al. 1982). Trees in some areas may compensate for early damage by increasing the size and weight of remaining nuts; in situations where rats feed on coconut flowers or damage very small nuts, yield losses may be underestimated by counts of fallen, maturing nuts.

Macadamia orchards in Hawaii and Australia sustain extensive damage from *Rattus rattus* (White et al. 1997, Tobin 1992). These arboreal rats gnaw through the hard shell to eat the developing kernel inside. Damaged nuts fall prematurely. Five to ten percent of developing nuts are damaged by rats in some Hawaiian orchards. However, the economic impact of this damage is not clear (Tobin et al. 1993), because some trees apparently partially compensate for this damage by producing additional nuts (Tobin et al. 1 997a).

Rodents in Africa, Asia, South America, and the West Indies open ripening pods of cacao and either take whole beans or feed only on the mucilage which surrounds the beans, depending on the species of rodent (Wood 1994). Damaged pods are lost due either directly to rodent damage or indirectly to ensuing fungus infection. Damage often is greatest where cacao is grown in mixed culture with other crops such as coconut (Williams 1973, as cited in Wood 1994). Depredating species include *Rattus tiomanicus, Rattus tanezumi,* and *Callosciurus notatus in Asia,* and *Hylomyscus stella, Praomys tullbergi, Stochomys longicaudatus, Dephomys defua,* and *Praomys morio* in West Africa (Wood 1994).

Commercial oil palm plantations in Malaysia and Africa sustain damage from rodents that feed in the crowns of trees on the oil-bearing tissue of developing fruitlets. Wood (1994) reported that populations of *Rattus tiomanicus* reached between 200 and 600 rats per hectare in Malaysian orchards where no rodent control was practiced, with estimated losses averaging about 5% of the yield. *Rattus argentiventer* and *Rattus tanezumi* sometimes also become pests in Malaysian orchards (Wood 1994). In Africa, the major rodent species causing damage to oil palms include: *Dasymys incomtus*, *Lophuromys sikapusi, Tatera valida, Oenomys hypoxanthus, Praomys morio, Mus minutoides, Lemniscomys striatus*, and *Uranomys ruddi* (Wood 1994). Up to 80% losses have been reported in Nigeria in one year (Wood 1994).

4.4. Stored Products

Rodent consumption of stored food and grain and damage to storage structures and containers, and indirect losses caused by spillage, spoilage, or contamination that results in condemnation or rejection of shipments are important economic and public health problems worldwide (Jackson 1977, Brooks and LaVoie 1990, Conover et al. 1995). The great diversity of rodent species, storage structures, and environmental conditions and the difficulty in estimating incremental or indirect losses help mask the economic impact of the problem. Since most rodent species involved in stored product damage are nocturnal, heavy infestations may persist unnoticed without careful inspection of stores or premises (Jackson 1990). In many situations, careful grain

handling procedures, indoor and outdoor sanitation, immediate disposal of spillage and garbage, frequent inspection for rodent signs, and maintenance control programs are important ways to prevent the development of more serious and difficult problems.

4.5. Forest Crops and Reforestation

Foraging by rodents can be a major impediment to reforestation efforts around the world. Direct predation on seeds by deer mice (*Peromyscus sp*.) and house mice (*Mus musculus*) in USA (Nolte and Barnett 2000) can preclude or reduce the success of direct seeding efforts. Clipping and girdling of the roots and stems of young seedlings by a wide variety of rodents is a major source of tree mortality. Pest species include: squirrels (*Sciurus sp.* and *Tamasciurus sp.*) strip bark from trees in Europe and North America (Gill 1992); voles (*Microtus sp*., *Clethrionomys sp*.) in the United States, Europe, and Asia (Myllymaki 1977, Pigott 1985, Maguire 1989); deer mice (*Peromyscus sp*.) in the United States (Maguire 1989); porcupines (*Hystrix indica*) in Asia (Khan et al. 2000) and (*Erethizon dorsatum*) USA (Wagner and Nolte 2000); pocket gophers (*Thomomys sp.*) in USA (Crouch 1986, Engeman et al. 1998a); and mountain beavers (*Aplodontia rufa*) in the Pacific Northwest (Wagner and Nolte 2000). In western USA pocket gophers (*Thomomys sp.*) damage or destroy hundreds of thousands of acres of forestland each year, severing stems and girdling roots and stems of more conifers than all other wild mammals (Crouch, 1986). Even when rodent control programs are in place, pocket gophers may quickly re-invade cleared areas and re-occupy vacant burrow systems (Engeman and Campbell 1999). Beavers (*Castor canadensis*) in North America, particularly in southeastern USA, also cause considerable damage to trees and forests as well as to landscape plantings, both directly by their feeding and dam-building activities, and indirectly by flooding caused by blocking streams and drainage structures with dams (Conover et al. 1995). Nolte and Otto (1996) have compiled analysis of tree damage by rodents and other wildlife species that provides current sources of management materials as well as a guide to identification of damage.

4.6. Hydraulic Structures

Although little has been published, a number of burrowing rodent species cause damage, water loss, and the attendant risks of flooding, by excavating earthen dams, irrigation canals, or flood control structures. Notable species involved are beavers (*Castor canadensis*), muskrats (*Ondatra zibethicus*), gophers (Geomyidae), and ground squirrels (*Spermophilus sp*.) in North America; *Bandicota bengalensis* in southern Asia; and nutria (*Myocastor coypus*) in North and South America. A variety of other burrowing species cause problems on a localized basis. Determining the cause of breaks in hydraulic structures is often difficult because animal activity is impossible to assess if the evidence has washed away. Failure to control rodent infestations, however, is potentially threatening to human life and may result in legal actions and repairs ranging to millions of dollars (Hegdal and Harbour 1991).

High beaver (*Castor canadensis*) populations in many areas are now a cause of considerable concern for both forest managers and for those responsible for flood prevention and control. These large rodents move to flowing water and cut surrounding trees by gnawing around the circumference of their bases. Trees are used for dam building, lodge construction, and food. Beavers also excavate dens in the banks of reservoirs, streams, or canals, resulting in water loss and even structural failure. Beaver dams that block culverts, ditches, streams, or spillways can result in extensive flooding and damage to bridges, roads, and other structures, as well as

flooding and death of trees in commercial plantations or reforestation and riparian areas (Hegdal and Harbour 1991, Conover et al. 1995, Fall and Jackson 1998).

4.7. Urban Rodent Problems

In most of the world's cities and towns, one or more of the cosmopolitan commensal rodents (*Rattus rattus, Rattus norvegicus,* or *Mus musculus*) live with people in homes, business establishments, markets, yards, and sewers. A variety of other species occur in parts of their ranges as commensal rodents in urban areas, notably, *Rattus exulans* and *Rattus tanezumi* in Southeast Asia, *Bandicota bengalensis* in southern Asia, and *Mastomys natalensis* in parts of Africa (Lund 1994). In close association with people in dense settlements, rodents cause a variety of problems, including loss and contamination of foodstuffs, destruction of property, rat bites, gnawed electrical wiring resulting in fires, and transmission of diseases, notably salmonellosis, but a variety of others in various parts of the world.

Because of their relative prominence, rodent infestations in urban areas generally attract political attention and become the frequent subject of periodic, large-scale control efforts. Davis (1972) contended, based on his research in Baltimore in the late 1940s (Davis 1953), that enough was known about rodent population principles to control urban rodent infestations and other rodent problems. His research demonstrated that outdoor rodent populations in cities could be managed by removal of the food and habitat on which Norway rat (*Rattus norvegicus*) populations depended. Fifty years later, Fall and Jackson (1998) saw the failure of this approach related to the difficulty in maintaining the diligence of urban residents and the inconsistent support of the public and private sectors. Colvin and Jackson (1999) maintain urban rodent control must focus on strategic, comprehensive approaches that incorporate multiple tactics and partnerships among government agencies, community groups, and pest control companies. Clearly, large-scale rodent control efforts in urban areas, if properly planned and managed using IPM approaches, can be quite effective (Colvin et al. 1990).

4.8. Damage to Cables, Wires, and Electronics

Various species of rodents gnaw on above- and under-ground communications and power cables, resulting in service interruptions, fires, and other safety concerns (Shumake et al. 1999, 2000; Cogelia et al. 1976). Seismic cables laid on the ground surface for geologic mapping are often damaged by rodents and other wildlife species. About 18% of telephone and 26% of electric manholes inspected in downtown Boston had evidence of rat (Rattus norvegicus) activity (Colvin et al. 1998). Ramey and McCann (1997) reviewed research conducted in USA since the 1940s to develop cables resistant to damage by rodents, mostly pocket gophers (*Thomomys sp.* and *Geomys sp.*). Much of this research evaluated either the susceptibility of various types of cable to gnawing (McCann 1995, Shumake et al. 1999) or the effectiveness of repellents for deterring gnawing (Shumake et al. 1999, 2000). Rodents living in attics, walls, and basements commonly gnaw electrical wiring, sometimes causing fires (Jackson 1990). Mice, in particular, may readily gain access to sensitive electronic equipment, damaging wiring and circuit boards.

4.9. Rodents and Disease

The list of diseases of humans and domestic animals for which rodents serve as vectors or reservoirs is long—and growing. Each decade sees new diseases described and new epidemiologic associations made to particular rodent species. The commensal rodents, particularly *Rattus rattus* and *Rattus norvegicus*, because of their close association with man, are

particularly important. Zinsser (1935) provided an interesting account of the historical importance of louse-borne typhus in decimating human populations and influencing the outcomes of human conflicts over several centuries. Gregg (1985) similarly recounts the historyand rodent-flea-human associations of plague pandemics, including the Black Death of 14th century Europe. Plague continues to be a disease of local concern in several parts of the world. Leptospirosis, another rodent-borne disease of worldwide importance to humans and domestic animals, has been recently reviewed by Faine (1994). Gratz (1988, 1994) provides comprehensive reviews of diseases and rodent species associations for which rodent control programs may be indicated as management measures. Detailed summaries of communicable diseases for which rodents are implicated as vectors or reservoirs, including symptoms, courses of treatment, and means of prevention are available in Chin (2000). Rodent control efforts that minimize close human and domestic animal exposure to rodent infestations, combined with surveillance and monitoring in local problem areas can help prevent rodent-borne disease outbreaks from becoming more widespread.

4.10. Conservation of Rare Species

Rats have had a devastating impact on many native ecosystems, particularly remote islands where the flora and fauna has evolved in isolation from predatory pressures (Atkinson 1989). Polynesian rats (*Rattus exulans*) spread with early Polynesian immigrants across the Pacific basin, and roof rats (*Rattus rattus*) and Norway rats (*Rattus norvegicus*) later accompanied western explorers throughout the world (Atkinson 1985). All three species prey on ground-nesting sea birds on remote oceanic islands (Austin 1948, Kepler 1967, Coulter et al. 1985, Bertram 1995). Roof rats, the only one of the three species that regularly climbs trees, prey on the eggs and young of many species of forest birds (Atkinson 1977, Dunlevy et al. 2000). Rats have negative impacts on rare invertebrate fauna (Hadfield et al. 1993) and on native vegetation (Allen et al. 1994, Witmer et al. 1998) on many islands, and may help spread seeds of invasive plant species (Dunlevy et al. 2000).

5. Control Methods

Many different methods for controlling rodents or rodent damage have been passed down through folklore or have been tested and proven effective in particular situations. Others are promoted or marketed as ultimate solutions to a gullible public, but are impractical or ineffective. Some materials or methods once widely used are no longer available, having been recognized as unsafe or fallen victim to increasingly stringent environmental regulations or changing cultural mores. Development of new rodent control methods continues to be an exciting subject for researchers. Fall (1990) summarized, in tabular form, the great variety of methods and techniques suggested, used, or tested for various rodent problems. Space allows us to discuss only a few of the diverse approaches to rodent control; however the references and additional reading provided will give an interested reader details on particular approaches.

5.1. Integrated Pest Management

The diversity of rodent pests and types of pest problems worldwide requires a variety of approaches for resolving site- and situation-specific problems. Controlling rat damage in Asian rice fields requires a different approach from that required for controlling the spread of diseases transmitted by rats in urban environments; controlling rodent damage to forest plantings in North

America presents a decidedly different situation from controlling depredations of rodents in African wheat fields. Smith and Calvert (1978) defined IPM as broad, ecologically based control systems that use and manipulate multiple tactics in an effective and coordinated way. Smith's personal, concise definition, "…an ecological approach to pest control," conceptualizes the actions required to manage the multiplicity of plant and animal pests, including rodents, that lower the efficiency of humankind's production systems or reduce the quality of life for people worldwide. In its broadest sense, integrated rodent pest management (IPM) is the utilization of a variety of control methods, appropriate to specific damage situations, emphasizing the use of environmental controls on population growth, and continuously evaluated in relation to achieving levels of damage that can be tolerated economically and socially, to resolve specific problems (Marsh 1981, Fall and Jackson 1998, Singleton et al. 1999). Decision support systems are available for a few rodent control problems (others are under development) that can help a user to process ecological information, evaluate the variety of options and techniques appropriate to the problem, and better predict when control actions need to be taken (Engeman and Witmer 2000).

5.2. Habitat Management

All animals require food, water, and cover to survive and reproduce. Where these resources are abundant, rodents thrive; where they are in short supply, animals either emigrate or die. Whenever possible, control programs should focus on altering the habitat and reducing its potential for attracting and supporting pest species. Otherwise, the effectiveness of rodent control measures will be of short duration and must be frequently repeated (Davis 1972, Engeman and Campbell 1999).

Rat (*Rattus sordidus* and *Melomys burtoni*) damage to sugarcane is a major problem in Australia. Traditional control measures that rely on widespread aerial application of toxic baits have resulted in highly variable success. The most effective control consists of herbicide treatments or early harvest and "trash-blanketing" to reduce in-crop weeds that attract rodents, combined with timely application of rodenticides (Hampson 1984, Whisson 1996).

In temperate areas, where voles (*Microtus sp.*) damage apple trees, particularly during winter, rodenticide baiting programs frequently have failed to prevent damage. Many commercial apple growers in USA maintain a vegetation-free zone under the orchard canopy to discourage voles from living near the bases of trees, where they cause the greatest damage. Many also mow orchard ground cover frequently during the growing season to discourage voles from residing in the orchard and to reduce vegetative competition with trees for water and nutrients (Tobin and Richmond 1993).

Wide-scale alteration of the habitat often is not feasible in tropical countries where critical resources are ubiquitous and available year-round. Open construction of housing and storage structures makes it possible for rodents to readily move from fields to buildings. The resources needed to apply herbicides or other means of reducing rodent habitat are often out of reach of people in rural areas or in dense human settlements lacking basic services and sanitation. The ecological consequences of major habitat alterations to reduce rodent infestations might be far-reaching, impacting desirable wildlife and the lives of human inhabitants in unacceptable measure.

In situations involving commensal rodents, every effort should be made to reduce food and cover that attract rats (Howard and Marsh 1981). This includes heavy pruning of ivy, palm trees, berry thickets, or any densely growing plants adjacent to structures, as well as maintaining sanitary conditions in homes, businesses, streets, and vacant areas. Garbage cans and industrial trash containers should have tight-fitting covers, and trash should be collected frequently. A general removal of all rubbish and trash helps reduce food and harborage for rats. The most effective means of limiting rodent damage in buildings and structures is to prevent their initial entry (Baker et al. 1994). Rats can crawl through or under any opening higher or wider 1.3 cm, and mice can gain entry through any opening larger than 0.6 cm. Both rats and mice can run along or climb electrical wires, pipes, fences, poles, ropes, cables, vines, shrubs, and trees, as well as climb almost any rough vertical surface such as wood, brick, concrete, weathered sheet metal, and many plastic products. Rats and mice can crawl horizontally along or through pipes, augers, conveyors, conduit, and underground utility and communications lines, as well as gnaw through a wide variety of materials, including lead and aluminum sheeting, window screens, wood, rubber, vinyl, fiberglass, plastic, and low-quality concrete block. Buildings should be inspected carefully to detect any potential entry points. Cracks and openings in foundations should be sealed, and all openings where water pipes, electric wires, telephone wires, sewer pipes, drain spouts, and vents enter a building should be tightly sealed to prevent rodent access. Doors, windows, and screens should be tight-fitting.

5.3. Traps

An amazing variety of traps, commercially available or constructed in homes or villages, are used in efforts to control rodents; the centuries-long search for "a better mousetrap" has not ended (Bateman 1971, 1979). Trapping is widely used by specialists for surveillance and monitoring of rodent infestations and is, perhaps, the most selective technique to remove individual rodents from problem situations. Although trapping is very labor intensive and requires skill to be used effectively, its relatively low cost compared to other approaches often makes it a primary method of choice for rodent control. Trapping is also utilized where non-target animals are an important concern or where use of toxicants or other more effective methods are prohibited. Regulated commercial harvest of some species of rodents for their furs has been a successful method used by wildlife managers for holding rodent populations in check so that they do not reach levels that inflict serious economic damage. In recent years, use of certain types of traps and trap-setting methods has been restricted in various countries, largely through the efforts of animal rights organizations that have viewed trapping animals as inhumane (Fall and Jackson 1998). This has particularly affected the management of larger rodents such as beaver (*Castor canadensis*), muskrat (*Ondatra zibethicus*), and nutria or coypu (*Myocastor coypus*), and in some areas control of smaller rodents such as gophers (Geomyidae). Procedures for trapping different species vary widely and considerable behavioral information on the species of concern in a particular habitat is often required. Assessment of the selectivity of particular traps is useful, since capture of other animals reduces trap efficiency and may affect populations Jackson (1990) outlines procedures for capturing rats and mice with snaptraps or "breakback" traps, cage traps, and glue boards. Trap densities must be adjusted to pest population levels and the home range size of the species involved; and traps must be placed where animals are active, such as along walls or under the shelter of grain pallets. Traps may be baited to attract animals to the triggering mechanisms or may be set to capture animals in the course of their normal movements by carefully choosing the set locations. Trapping generally is not practical for

managing large infestations or removing entire populations over extensive areas. However, traps can be used effectively in limited areas or where substantial resources are available and more efficient techniques cannot be used or developed. Gosling and Baker (1989), for example, describe successful, sustained efforts over many years by British government biologists using leghold and cage traps to eradicate populations of muskrats and nutria.

5.4. Rodenticides

Toxicants frequently are the most practical and cost-effective tools for reducing troublesome rodent populations over large areas. Rodenticides require minimal manpower to apply and, when properly formulated and applied, have the potential to provide quick results with minimal impact on the environment and non-target animals. The effectiveness of rodenticide treatments varies considerably among toxicants, bait formulations, methods used, and timing of application. Fast-acting, single-feed toxicants like red squill, sodium fluoroacetate, strychnine, and zinc phosphide have the potential for rapid knock-down of the pest population, although success often declines with repeated applications because animals that survive quickly learn not to eat the bait. The naturally cautious behavior of many rodents helps them to survive poisoning campaigns. For this reason, repeated applications of fast acting, single feed rodenticide baits often are futile. Pretreatment with non-toxic bait, or "prebaiting", is often used to help overcome this problem.

Alternating toxicants and bait materials can also help forestall the development of bait shyness. The development of anticoagulant rodenticides during the late 1940s was a major advance in rodent control. At the concentrations used, first generation anticoagulant rodenticides, such as warfarin, pindone, fumarin, coumafuryl, diphacinone, and chlorophacinone, usually had to be consumed for several days for rats to receive a lethal dose. The delayed onset of sickness, together with the small amounts of the toxicant in baits effectively eliminated the problem of bait shyness. These low concentrations, coupled with their slow action and the availability of antidotes to reverse the anticoagulant effect, made these rodenticides very safe for human use. Second generation anticoagulant rodenticides, such as brodifacoum, bromadiolone, difenacoum, and difethialone, were developed during the 1970s and are much more toxic, usually requiring only a single feeding by commensal rodents for ingestion of a lethal dose. Genetic resistance to anticoagulant rodenticides emerged as early as 1958 and continues to be a concern with second generation anticoagulants (Buckle et al. 1994). The increased toxicity and biological persistence of some second generation anticoagulants has also raised regulatory concerns about environmental and human health effects, although these materials are also viewed as safe and are commonly available for household rodent control by untrained people. Stringent regulation of rodenticide use in many countries, however, has increased the costs of developing new materials and restricted the kinds of problem situations where rodenticides may be used (Fagerstone et al. 1990); a number of the older materials are no longer marketed. Use of some rodenticides may be allowed only by trained specialists.

The failure of many rodenticide baiting programs results not from bait shyness or resistance to toxicants, but because of improper application of bait. Rodenticide baiting programs used by some Hawaiian macadamia growers were ineffective because rats spent most of their time in the orchard canopy and rarely consumed baits that were broadcast on the orchard floor (Tobin et al. 1997b). In Philippine coconut orchards, crown-baiting, as opposed to ground applications, selectively targeted the specific individual animals active in tree crowns that caused damage to developing coconuts (Fiedler et al. 1982). All available rodenticides are poisons that must be

used with great caution. Package directions for use and pesticide labels must be carefully followed. When rodenticides are used for large-scale rodent control programs, local health authorities must be notified of the materials being used so that accidental poisoning cases can be readily diagnosed and treated.

5.5. Biological Control

Biological control, or the introduction of predators, parasites, or disease organisms to control pests, is an ecologically and conceptually appealing approach to reducing rodent pest populations. This tactic has been used successfully in many insect IPM programs to control insect crop pests. However, the principles and parameters relevant to insect IPM measures should not be applied unquestioningly to vertebrate pest problems (Marsh 1981). Introducing biological agents to control rodents is a promising area for research, but many challenges remain to find a candidate which is sufficiently pathogenic to achieve the desired level of control, has a high transmission rate, and is target specific (Singleton and Redhead 1990). We know of no examples of the successful introduction of predators or diseases that have been effective in preventing damage by rodents. Often, such attempts have not only been ineffective, they have resulted in serious environmental problems.

The role of natural predators in controlling rodent pests is an interesting, but frequently misunderstood, concept that rarely is effective in reducing pest populations to tolerable levels (Howard 1967, Hygnstrom et al. 1994). Numerous studies have demonstrated the importance of rodents in the diet of selected predators and have encouraged the establishment of predator populations in crop areas (Lenton 1980, Hall et al. 1981, Duckett 1982), but few have critically evaluated the utility of such predation for reducing pest populations or increasing crop yields. Fall (1977) observed that most predators in rice fields patrolled dikes, rather than entering wet paddies where rats were active. Or they congregated around fields after harvest when crop damage had already occurred and rats had no food or cover. Interest in fostering barn owl (*Tyto alba*) populations in oil palm plantations continues as a potential way to reduce rodenticide use. The introduction of barn owls to Hawaii for rodent control in the 1960s was ineffective.

Successful introduction of exotic vertebrate predators into new areas for pest control purposes has never been demonstrated and, in some cases, has resulted in unanticipated, calamitous ecological effects. During the late 1800s, the small Indian mongoose (*Herpestes javanicus*) was introduced into both the West Indies and Hawaii to control rat populations in sugarcane fields. Although this predator survives in some areas on a diet composed mainly of rats (Baldwin et al.1952, Kami 1964), the introductions failed to achieve the desired result of reducing rat populations in sugarcane fields. In both the West Indies and Hawaii, mongooses have severely impacted ground-nesting bird species by preying on their eggs and young (Ebenhard 1988). In some areas in the Caribbean, the species has become a reservoir for rabies. Most studies that have investigated predator-prey relationships have concluded that predators exert a controlling influence on their prey only under rare circumstances, such as when prey populations are already at low densities and alternative prey are scarce. More commonly, the presence of high rodent or other prey populations attracts and sustains predators which relocate when prey animals become more difficult to find and capture. Thus, except under rare conditions, predators do not hunt their prey to the low levels required for effective management of rodent damage.

Where rodent populations present health hazards for humans or domestic animals, they must be maintained at very low levels to minimize exposure risks. In such situations, disease organisms

or parasites may have difficulty sustaining infection unless an alternative host population exists (Davis et al. 1976). Davis and Jensen (1952) released *Salmonella enteriditis* into a population of Norway rats (*Rattus norvegicus*) and observed only very restricted spread of the infection and a likely development of resistance among the rodents. They concluded that the introduced disease was not effective in lowering the rat population. In another study, Singleton et al. (1995) released the nematode parasite, (*Capillaria hepatica*), into wild populations of house mice (*Mus musculus*) and concluded that the parasite could not limit low-density mouse populations. Many of the diseases and parasites to which rodents are susceptible are readily transmitted to humans and domestic animals, indicating the need for great caution in considering the use of such approaches for rodent control.

5.6. Reproductive Inhibition

Reproductive inhibition, in theory, would seem to be a useful method of reducing rodent populations. The rapid reproductive potential of most rodent species often enables them to rapidly overcome other population reduction measures. Reproductive inhibition is a non-lethal alternative that has the potential to provide long-lasting control. During the 1960s and 1970s, researchers explored the potential of various chemosterilants such as synthetic steroids, estrogens, and progestins as reproductive inhibitors (McIvor and Schmidt 1996). More recent research has focused on immunocontraception as a means of inducing self-sterilization in pest populations (Miller et al. 1998). However, to date the only successful use of wildlife reproductive inhibitors has been in laboratories, pens, and limited field situations, where animals are either captured, treated, and released, or are injected with darts at close range (obviously impractical for small, nocturnal mammals). The effective control of free-ranging wildlife populations would require oral delivery systems or species-specific, infectious carriers that could deliver reproductive inhibitors to a sufficiently high proportion of animals to effect population control. The technologies for achieving such delivery systems are still being researched. The ultimate development of reproductive inhibitors for controlling free-ranging wildlife populations will require the resolution of many complex legal, biological, economic, and ethical issues (Guynn 1997), and may be practical only for long-lived animals with lower reproductive capacities.

5.7. Ultrasonics

Many devices that emit high-intensity ultrasound (sound frequencies greater than 20 kHz) have been marketed for rodent control, usually with a claim that the ultrasound is aversive to rodents or somehow interferes with their communication. However, many studies that have evaluated ultrasound as a practical means of rodent control have concluded that ultrasound has only a partial or transitory effect (Shumake et al. 1982) or no effect at all on target species (Howard and Marsh 1985, Lund 1988, Bomford and O'Brien 1990). Jackson (1990), citing work by McCartney and Jackson (1986, 1988), contended the use of ultrasonics may be appropriate in some IPM programs to displace rodents from sensitive areas in structures to locations where traps or bait stations can be used. He cautioned that users of this tool need to be conversant with the technology.

5.8. Bounties and Insurance

Bounties, or payments for carcasses or body parts of rodent pests, have frequently been used in many parts of the world in attempts to reduce rodent populations or to induce public participation

in rodent control programs. Despite their widespread use, we know of no instances where bounties have succeeded in achieving the desired result, the reduction of pest populations to sufficiently low levels necessary for damage management purposes. Like wild predators, people often participate in bounty programs as long as animals are relatively easy to capture. However, as the pest population declines or as animals become more wary or difficult to capture, participation wanes. Because of rodents' high reproductive capacity, populations recover very quickly if conditions remain favorable. From an economic standpoint, it is not in the interest of participants in bounty programs to eliminate a source of income (the rodent population). Commonly, in areas where bounties are in effect, people are tempted to introduce breeding animals into the control area, to release mutilated animals, or to submit carcasses or body parts from other areas where animals are more easily collected.

Residential or business insurance policies sometimes cover property damage, fires, lost shipments from contamination, or other losses attributed to rodents if negligence is not involved. Insurance has not, however, been found to be a practical solution for dealing with crop losses caused by rodents, because of the statistical difficulties in relating damage that accumulates over the crop period to yield loss, because of the intermittent occurrence and unpredictability of damage, and because of the high costs of administering such programs.

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