13 Rodent Control in Practice: Tropical Field Crops

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Introduction

This chapter is a revision and update of material presented in the first edition (Fiedler and Fall, 1994). In 1994, we believed that examples of long-term successes in reducing rodent damage to tropical crops were very limited. At the time, the situation was blamed on insufficient information that had, over previous decades, precluded specific recommendations. Beginning in the late 1960s, several research projects, primarily focused in Asia, investigated important crop loss situations and demonstrated several effective rodent-control methods. Moreover, these findings and some control recommendations were published and incorporated into extension programmes in a number of areas. Most of the publications concerned were in widely available 'grey literature' or in conference proceedings because few journals were available with an interest in applied vertebrate pest control research – and even those were not available to managers, researchers or extension personnel in problem areas. Despite this progress in the development of rodent-control methods, the adoption of new methods by farmers has been slow, even in areas where intensive efforts were made to introduce new procedures (Quick, 1991). Problems associated with changing traditional rodent-control practices paralleled those encountered with the introduction of other new crop production technologies to tropical agriculture.

In updating our chapter, we searched the literature published since the 1994 edition, using the databases 'Wildlife & Ecology Studies Worldwide' and 'Google Scholar'. We used the search terms 'rat control' and 'rodent damage control', successively combined with 'cacao, cocoa', 'coconut', 'fruit', 'maize', 'corn', 'oil palm' and 'rice'. Because much of the post-1994 literature on rodent control in tropical crops has been generated by just a few investigators and their colleagues, we also searched selectively by author names and further searched the Rice Bibliography of the International Rice Research Institute (IRRI). Collectively, these searches resulted in several hundred thousand entries, though of course, with much redundancy. We examined the first 100 entries in each search, removed redundancy, then further eliminated papers that by title or keywords focused on damage observation or description, strategic or philosophical discussion, or anecdotal or promotional material rather than on the evaluation of actual control methods. We added several older papers to the list that we did not examine in 1994, resulting in about 200 new publications that we then read for content. We were surprised that relatively few papers focused on the practice of rodent control compared with the large number devoted to describing an already well-known problem of rodent damage to crops or promoting anti-pesticide approaches to problem resolution.

Practical rodent pest management methods are now available for tropical crops in many areas, usually involving combinations of cultural practices and the strategic use of environmentally safe rodenticides. However, rodent species differences and ecological differences in crops and cropping practices in different areas still require the evaluation of methods in new practical use situations (Wood, 2001). In our earlier review, published work on rodent control, a reflection of the overall research effort, was minimal, particularly in Central and South America, the Caribbean, Africa, the Middle East and the Far East (Kaukeinen, 1987). While the amount of new, practical information has increased somewhat, most current work continues to emphasize problem description or re-description rather than moving forward with the development of new practical rodent-control methods, thus leaving the continuing use of rodenticides the primary method of rodent damage control (Buckle, 1999; Singleton *et al.*, 1999a; Stenseth *et al.*, 2003). Although relatively more publications, particularly on African rodent damage problems, have appeared (Leirs and Schockaert, 1997; Makundi *et al.*, 1999), there are still a number of important crop damage situations for which no generally accepted rodent-control methods appear to be available or widely used (ICRBM, 2006).

Rodent Problems

Annual chronic losses

Rodent damage situations can be highly variable, often seasonal, unevenly distributed and difficult to predict (Fiedler *et al.*, 1991). Many rodent species are inactive during the day and are, therefore, not readily observed by farmers, extension workers or researchers. Damage can be concentrated and obvious, such as the 1–2 m diameter circles of cut wheat tillers surrounding burrow openings of bandicoot rats (*Bandicota bengalensis*); or it can be widely dispersed and cryptic, as in rice fields in South-east Asia with less than 10% damage. The latter damage pattern frequently goes unobserved by both farmers and crop protection specialists unless they examine plants closely.

The perception of a problem and of the actual damage or loss occurring can be very different, erring in either direction. For example, farmers in Indonesia appeared to be satisfied with their harvest before learning that their rice fields actually had more than 7.5% cut tiller damage and 0.64 t ha^{-1} lower yields than fields baited with rodenticides (Buckle, 1988). Also, without the benefit of actual damage assessments, crop protection specialists and Filipino farmers disagreed on the pest status of rodents in rice fields (Litsinger *et al.*, 1980). These examples demonstrate the importance of the physical examination of individual plants to assess rodent damage and the need to examine yield losses.

Estimating crop damage and relating the results to yield loss is often confounded by variations caused by plant compensation and different fertilizer inputs, insect pest and weed problems, and inadequate damage assessment techniques (see Chapter 10). Nevertheless, chronic losses that occur annually in tropical field crops as a result of rodent damage are probably 5% or more (Hopf *et al.*, 1976), even when traditional rodent-control methods are practised. Locally, chronic losses can be much higher (Jackson, 1977), particularly when crops are grown in areas that are highly susceptible to rodent damage. When these chronic losses occur continually over large areas, they are more significant than the more obvious outbreak losses that receive national, and sometimes international, attention (Buckle *et al.*, 1985; Leirs *et al.*, 1999; Stenseth *et al.*, 2003).

Periodic acute losses

Outbreaks of losses in agricultural areas that result from unusual rodent population increases can be dramatic and extremely visible, and can occasionally result in food shortages over large areas. There are two primary types of rodent population outbreaks. One type occurs after new areas are opened to agricultural production; another type results from major climatic changes involving a period of either excessive rainfall or, more commonly, abnormal drought followed by normal rainfall (Fiedler, 1988b; Leirs *et al.*, 1990; Singleton *et al.*, 2010a). Lengthy drought not only reduces rodent populations but also changes the influence of factors that normally limit their numbers – predation, competition and disease. Resumption of rainfall provides an immediate abundance of food, shelter and water for surviving rodents, so that increased reproduction, survival and dispersal occur. Rodent outbreaks in Australia and Hawaii involving *Mus musculus* occur after lengthy droughts are ended by normal rainfall (Tomich, 1986; Ramsey and Wilson, 2000). Australian wheat crops have been seriously affected during these mouse plagues (see Witmer and Singleton, 2010; and Chapter 12). Rat population irruptions involving bamboo flowering are related in that abundant food becomes available in areas with previously limited resources (see Chapter 3). As the food base again declines, surviving rodents may shift their activity ranges into cropping areas (Jaksic and Lima, 2003; Singleton *et al.*, 2010b).

Reports of rodent outbreaks in Africa have been more frequent, extreme and widespread than in other tropical areas. Two or more periods of favourable rains, after a period of low rodent population density resulting from drought, characterized outbreaks in Senegal (Hubert and Adam, 1985; Leirs *et al.*, 1990, 1996). Similarly, the 1986–1987 outbreaks in Sudan and some other Sahelian countries occurred after a 4–7 year drought was interrupted by normal rainfall in 1985 and 1986 (Fiedler, 1988a). Over a 12–18 month period, high rodent populations developed but went unnoticed by authorities until complaints from farmers reached a peak. In remote areas, subsistence farmers were forced to replant fields several times before any assistance was begun.

Common characteristics of tropical rodent problems

Although each tropical rodent damage situation deserves individual attention, there are some general characteristics that are shared. Most rodent pest populations express seasonal trends in activity, reproduction and abundance which are related to crop phenology and climate. Alternating dry and wet seasons influence not only crop planting schedules but also rodent breeding, mortality and mobility. Successful damage control programmes have identified these seasonal trends and used the information to help determine when crops are most susceptible to damage and when rodent pests are most susceptible to control. Because habitats adjacent to crop fields, orchards or plantations generally provide food and cover throughout the year, rodents may breed continuously in these areas, invading fields when crops are susceptible to damage. Such refugia may present special problems of access and the exposure of non-target animals if rodent control is attempted outside field margins.

When habitats are disrupted, resident rodents may move to more favourable surroundings. Disruptions may be caused by fire, flooding (including patterns of irrigation), drought and agricultural practices such as land preparation and harvesting. During dry seasons, irrigated croplands attract rodents from surrounding, less favourable habitats. Knowing how adjacent habitats influence rodent damage in susceptible crops is essential for effectively managing rodent pest problems.

Control Methods

The primary objective in any agricultural rodent pest management programme should be cost-effective crop protection, hence lower damage and higher yields. Using numbers of rodents or indices of rodent abundance before and after control operations is only useful for determining changes in populations or activity. Unless it has been adequately demonstrated that reduced populations result in reduced damage in a particular situation, changes in rodent numbers should not be relied on to estimate the degree of crop protection achieved. Even though reducing local populations may achieve higher yields in many situations, in some, the yield increase may be relatively costly. For example, crown baiting in Philippine coconut plantations is more cost-effective than ground-baiting methods (Fiedler *et al.*, 1982). Targeting those rodents that are actually doing the damage increases efficiency and raises the economic benefits of control by lowering costs. Effective control programmes have been based on ecological or behavioural research that identified the vulnerable factors in the behaviour and life cycles of rodent species and have used this information in the development of materials, methods and procedures to protect crops. For example, sustained baiting to protect rice from rodent damage involved adjusting the numbers and locations of bait stations to manage feeding competition and relate bait presentation to crop stage and damage potential (West *et al.*, 1975; Fall, 1977; Hoque and Sanchez, 2008).

Many rodent-control problems involve only a single pest species. Further, in multiple species situations, it is possible for a minor rodent species to assume a greater role in crop damage when populations of a primary species are reduced or when seasonal habitat changes no longer favour the primary species (Wood, 2001). For a situation involving rodents and larger mammals, such as bandicoot rats and golden jackals (*Canis aureus*) inhabiting Bangladesh sugarcane fields (Sultana and Jaeger, 1992), a systems management approach may be helpful (Watt, 1970). However, systems approaches are expensive and time-consuming to develop and, without widespread adoption, the development costs would probably not be recovered (Hygnstrom, 1990).

Chemical

Rodenticides are generally an integral part of successful rodent pest management and, in some tropical habitats, are the only practical method available (Buckle, 1999). Unfortunately, farmers and extension personnel are often confused or uninformed as to how a particular product may be effectively used. Local labels typically lack adequate use directions and provide only generic instructions that leave users guessing or improperly improvising untested application methods. Fortunately, a number of companies that service international rodenticide markets are now providing better information and technical assistance for tropical countries.

There are two basic field methods currently recommended for applying rodenticide baits. Both the sustained baiting method, with multiple-dose anticoagulants, and the pulsed-baiting method, with single-dose anticoagulants or acute rodenticides, can be cost-effective in specific crop situations (Wood, 2001; Wood and Chung, 2003). Sustained baiting, developed in the early 1970s (Fall, 1977), is still recommended for reducing rodent losses to rice-field rats, even when damage levels are low (Reissig *et al.*, 1985; Singleton and Petch, 1994; Hoque and Sanchez, 2008). The technique initially requires a continuous, low-level input of bait which is monitored and supplemented as rodenticide bait consumption increases during the crop season, and then terminated before harvest. Costs are, therefore, related to the actual risk of damage and the unnecessary use of rodenticide is avoided, and the approach has been even more profitable to farmers in areas susceptible to significant losses.

Pulsed baiting promotes the application of second-generation anticoagulant rodenticides at intervals designed to reduce the amounts of labour and bait material used. Because of the greater toxicity of second-generation anticoagulants, they are generally sold to farmers as end-use products rather than as concentrates. Acute rodenticides, such as zinc phosphide, can also be applied at intervals, but often require prebaiting or other tactics to achieve a similar effect and, in stable rat populations, bait shyness may become a problem. The interval between baiting pulses may be as short as 1 week (Dubock, 1982; Buckle *et al.*, 1984a), or as long as 6 months (Advani and Mathur, 1988), depending on the rodent problem and the control objectives. End-use products with pre-formulated bait entail substantially higher costs, because the transportation of products, particularly those originating offshore, includes shipment and distribution costs for inert bait base material. While rodenticide concentrates are preferable for farm use, pre-formulated baits may be safer, easier to handle and still cost-effective if used properly (Ahmed and Fiedler, 2002). For some rodent species that hoard food, the use of loose bait is preferable, as animals may move prepared baits without consuming them.

Chemical repellents or those derived from predator urines, capsaicin or other natural products are often suggested as having the potential to reduce rodent damage to crops, and considerable research effort has been engaged on this approach for many years (e.g. Mason *et al.*, 1996). Nevertheless, repellents have, as yet, found very limited practical application (Mason, 1997, 1998; Tobin *et al.*, 1997) and are a particular concern if consumable portions of food crops hold potentially irritating or toxic residues. Limited success has been found with repellents for seeds, seedlings or tree crops browsed or girdled by rodents (Mason, 1997; Ngowo *et al.*, 2005).

Non-chemical

Non-chemical methods can be used alone or integrated with rodenticide use when practical and cost-effective. Continuing research efforts are clearly needed so that effective rodent damage control is less dependent on the use of rodenticides as a primary method (Leirs *et al.*, 1999). However, the continuous availability of food (including crops), water (irrigation in dry seasons) and shelter (prolific vegetation) maintains rodent populations in and around tropical agricultural fields and often limits the apparent effectiveness of physical and biological approaches to controlling crop damage.

In some situations, predators have been shown to have an impact on pest populations (Newsome, 1990) but, more commonly, the presence of vertebrate predators in crop areas generally reflects the presence of pest rodents (Howard, 1967). Despite abundant prey populations when crops mature, and for fleeting periods after harvests, it appears that most potential rodent predators do not maintain functional populations on a permanent basis in monotypic agricultural fields (Fall, 1977; Tobin and Fall, 2005). Nonetheless, artificial increases in predation have been periodically promoted as a method of rodent control, the most well-known attempt being introductions of the mongoose (*Herpestes javanicus*) to sugarcane-producing areas in the tropics during the late 1800s. Although these introductions were not successful in reducing rodent damage, they had long-lasting and unfortunate impacts on ground-nesting birds and provided a continuing reservoir of wildlife rabies. The excellent cover provided by field crops and the long intervals when fields are fallow between crops preclude the effective establishment of predator populations in many crop areas. Nevertheless, this approach continues to be investigated. Recent efforts have included the provision of artificial raptor perches or nesting structures and attempts to increase predator abundance, but field trial data to establish the effectiveness of such measures in increasing crop yields are lacking or inconsistent (Howard *et al.*, 1985; Askham, 1990; Smal *et al.*, 1990; Chia *et al.*, 1995; Wood and Chung, 2003; Witmer *et al.*, 2008). Notwithstanding, locally active rodent predators in farming areas should be maintained, and control programmes should be designed to minimize impact on predators and other desirable wildlife.

Barriers or fences have been effective in local situations. Inchaurraga (1973) used sheet metal barriers in South American rice fields to obtain a 5 t ha^{-1} yield compared with only 2 t ha^{-1} in unprotected plots. Shumake *et al.* (1979) demonstrated that non-lethal electric barriers could stop rat damage to rice plots, with impressive yield increases, and interrupt the activity sinks that occur when rodents are killed in large numbers on small areas (Uhler, 1967; Ahmed and Fiedler, 2002). Barriers are commonly used to protect more valuable crops, such as seedbeds or research plots. Unfortunately, some methods are hazardous and have killed humans, livestock and other non-target species. Quick and Manaligod (1991) reported 11 human fatalities in one area of the Philippines resulting from the use of 220 V electric wires strung from main lines to protect rice fields. Research on barrier methods continues and may yet result in more broadly useful techniques.

Trapping is usually not practical if rodents are numerous, affected areas too large, traps costly or reinvasion rapid. If traps are used, the intensity of effort needs to be related to the numbers and activity of rodents and compared with the level of crop damage. Usually, trapping has proven to be so labour intensive that little benefit is achieved or efforts cannot be maintained because farmers lose interest when local rodent activity is low before crops are susceptible. Still, in some special situations, for example experimental fields of deepwater rice (Islam and Karim, 1995), trapping has been used effectively to manage rat damage.

Lam (1988) and Lam *et al.* (1990) combined simple drift fence barriers and traps to prevent invasions of Asian rice-field rats (*Rattus argentiventer*) into substantial areas of susceptible rice. At IRRI, Singleton and numerous colleagues have refined this approach and used it as a means to improve community-wide approaches to rodent capture for the protection of rice crops (IRRI, 1992; Singleton *et al.*, 1998, 1999c). More recent research has demonstrated applications in various rice production systems (dela Cruz *et al.*, 2003; Sudarmaji *et al.*, 2010).

Habitat manipulation appears to have more potential in temperate, urban areas than in tropical crops (Colvin, 1991), though for some tropical crops, changing certain portions of agricultural habitats could be beneficial, and this approach at least bears further evaluation (Whisson, 1996; Horskins *et al.*, 1998; White *et al.*, 1998; Jacob, 2008). Wood (1991) noticed two distinct cultural practices in Malaysian rice fields that could account for major differences in rice yield and rodent damage. Large northern paddies with smaller and fewer bunds provided fewer nesting sites and less weedy shelter for Asian rice-field rats than did southern paddies with larger, more numerous bunds. Wood speculated that modifying the bunds in the south might result in lower damage. Weeding within and adjacent to field crops can also reduce rodent cover and damage (Hoque and Olvida, 1986), a concept understood by farmers using very traditional crop production methods (Litsinger *et al.*, 1982).

Synchronous planting shortens the period that crops remain susceptible to damage and reduces the chance of early- or late-maturing fields becoming focal points of rodent activity. However, labour shortages during the brief transplanting and harvest periods (for example, Wood and Chung, 2003) and the progressive availability of water in areas that use gravity irrigation may preclude synchronous planting.

Control Programme Organization

In any rodent damage control effort there are three basic strategies to choose from: tolerance of the damage, management of the damage, or eradication of rodents. Tolerance is practised by both farmers and government officials. It is usually selected because of apathy, a lack of awareness of crop damage, unfamiliarity with other options, or because of religious, social or legal taboos against harming animals. Tolerance may be useful when control requires more effort and cost than simply accepting crop losses. Permanent or temporary eradication of rodents from crop areas is generally not practical or ecologically sound. Large-scale rodent-control campaigns have often been based on the false premise that rodent eradication from crop areas was possible.

The most practical strategy is the management of crop damage. Whether for a large commercial grower, a research farm or an individual farmer, a management strategy should determine a minimum amount of damage or loss that can be accepted (Fall, 1991). Drummond (1991) presented a four-part management concept consisting of: (i) an objective leading to (ii) a plan for implementing (iii) actions or activities that are subject to (iv) an evaluation to determine the level of success. The objective should not be to reduce rodent populations, but rather to reduce damage, increase yield or lower rodent-borne disease to some predetermined and acceptable level.

Two general approaches to organizing rodent damage control programmes have been used. The first, the area-wide or community-based approach, with its origins in the urban rodent-control programmes of temperate countries, is clearly difficult to organize and maintain for tropical field crop situations owing to small farm sizes and high human populations. Such programmes (frequently built around external donor assistance) tend to foster bureaucracies that are more responsive to the vagaries of local politics than to protection of crops. However, area-wide programmes can be effectively organized when governments have the authority to demand, or the influence to attract, farmer participation (Sumangil, 1991; Leung *et al.*, 1999; Sudarmaji *et al.*, 2010). Rural communities, farmer cooperatives or other farmer organizations often provide an existing framework within which rodent-control activities can be introduced and implemented. In some situations (plantation crops or large holdings), large-scale rodent-control programmes must be handled by one individual or organization. The pulsed-baiting method for rodenticide use, which relies on area-wide applications, has been used effectively in these latter situations (Buckle, 1988; Wood, 2001; Ahmed and Fiedler, 2002). Smaller quantities of rodenticide bait applied at more locations but at longer time intervals provide adequate protection with less effort than do sustained baiting or other farm-based programmes, but this technique loses some advantage when adjacent farms do not participate or when the immigration of rodents is rapid. When large-scale programmes are appropriate, careful attention to early warning and surveillance procedures, the timing of treatments in relation to crop susceptibility, full participation of the affected community and the monitoring of crop damage are essential elements for effectiveness. Singleton *et al.* (1999c) have investigated and refined similar tactics using trap-barrier systems.

The second approach places responsibility for rodent control with individual farmers. This requires that each farmer must obtain materials needed and carry out rodent control in his own fields. Extension workers may assist by providing specific information and recommendations, but government personnel need not become directly involved in rodent-control operations except during major population outbreaks. Individual responsibility is a relatively new approach in many tropical countries. Farmers who have relied on government programmes in the past are reluctant to take individual initiatives. This constraint will probably continue until methods and materials are developed that are widely available for individual use at appropriate times, until effective means are available to inform and train farmers, and until national governments and donor organizations cease to promote subsidized area-wide programmes. The development of such individual farmer approaches in the Philippines in the 1970s made rodent control in rice fields parallel to other Green Revolution technologies, such as: the use of certified seed, fertilizer and irrigation; insect, disease and weed control; and advanced cultural practices (Reissig *et al.*, 1985; Hoque and Sanchez, 2008).

Primary Rodent Pests

Seven genera of rodents are responsible for most crop damage in tropical situations and these have been identified for the specific attention of international donors (Drummond, 1978). These genera range over wide areas, with some overlapping of continents. Consequently, they have received the most attention by international and national research and development programmes, and have the most information available about effective control practices. Singleton *et al.* (2010a) and Witmer and Singleton (2010) have identified numerous other rodent species, less widely distributed, that may sometimes cause serious crop damage. In this chapter, our names follow those used by Wilson and Reeder (2005) in *Mammal Species of the World*, except when we mention older names (which we have tried to clarify) or quote directly from other authors (particularly in the References section). A number of rodent names have changed since we first wrote this chapter in 1994, and many authors continue to use old names or variants, thereby causing considerable confusion in the rodent-control literature.

In 1994, we constructed range maps for important species and genera based on distribution information reported in the 1993 edition of Wilson and Reeder. Here, we refer the reader to online range maps constructed by the Global Biodiversity Information Facility (http://www.gbif.org), a multinational organization headquartered in Copenhagen, Denmark, that compiles current information, including range maps, based on specimen holdings in major international museums.

Rattus spp. (rats)

The genus *Rattus* (see range map at http://www.gbif.org/species/2439223) ranges worldwide and includes about 56 species, although only a few have adverse impacts on man. These rodents typically are generalists, exhibiting broad food and habitat preferences. They are the most abundant mammal as well as the most economically important rodent present in many countries. The most familiar are the Norway rat (*R. norvegicus*, which is not a species of primary tropical concern; see range map at: http://www.gbif.org/species/2439261) and the roof rat (*R. rattus*, range map at: http://www.gbif.org/species/2439270), which cohabit with humans nearly everywhere. Occasionally, they have adapted to living in agricultural fields (for example in crops in Hawaii), but crop damage is usually ascribed to other, less commensal species. Some subspecies of *Rattus*, such as the Philippine rice-field rat (*R. r. mindanensis*, now *R. tanezumi*; see range map at: http://www.gbif.org/species/2439262), are true field pests and, even though they may be opportunistic commensals, they thrive in the absence of dwellings. Introduced commensal rodents have disrupted the biodiversity on many islands throughout the tropics (Atkinson, 1985; Chapter 18) and attempts to eradicate *Rattus*, even on small islands, have required massive, labour-intensive efforts (Moors, 1985; Howald *et al.*, 2007), and often considerable precedent efforts, to assure regulatory compliance in such projects (Pitt *et al.*, 2011).

In addition to *R. rattus* and *R. tanezumi*, other species (*R. argentiventer*, *R. exulans*, *R. nitidus*, *R. losea* and *R. tiomanicus*) are present in various parts of Asia and the Pacific Basin where they may damage rice, oil palm, coconut, maize and a wide variety of other crops (Williams, 1985; Hoque *et al.*, 1988; Chapter 3). *R. tiomanicus* has been a chronic pest of ripening oil palm fruit in Malaysia, where resistance to warfarin has required the use of second-generation anticoagulants in control operations. *R. r. diardii* (now *R. tanezumi*), previously known primarily as a commensal species, has more recently become common in some oil palm plantations that are far removed from dwellings (Wood and Chung, 1990; Wood, 2001). *R. villosissimus* periodically irrupts and causes extensive crop damage in Australia.

Since Wood (1971) realized that Malaysian rice yields could be experimentally increased threefold with rodenticide baiting during the crop period, equally dramatic results have been achieved in Indonesia and Philippine rice fields. The costs of control efforts can usually be economically justified if yield losses exceed 0.5% (Buckle *et al.*, 1984b), but without effective control, average losses from rodent damage in field crops are usually much higher. Research has identified rodenticide formulation, bait placement and the timing of bait applications as key factors that determine the effectiveness of crop damage control. Timing proved to be most important when two formulations of warfarin were compared for controlling *R. argentiventer* damage to Malaysian rice (Buckle *et al.*, 1980).

Baiting begun shortly after transplanting and continuing for at least 4–8 weeks was more effective than other baiting schedules tested. Research in Philippine rice fields on *R. r. mindanensis* (now *R. tanezumi*) and *R. argentiventer* showed that it was critical to begin baiting early in the crop cycle and to distribute bait points within paddies instead of at central locations on dykes (Fall, 1977) in order to reach all individuals and assure that the rats actually causing the damage can access bait. The technique has been widely used (Reissig *et al.*, 1985; Singleton and Petch, 1994; Hoque and Sanchez, 2008) and has been adapted to work effectively in other crops (Fiedler *et al.*, 1982).

Bandicota spp. (bandicoot rats)

Bandicoot rats (see range map at: http://www.gbif.org/species/2437726) are major rodent pests in the irrigated crop fields of India (Prakash and Mathur, 1988; Mathur, 1997), and also cause significant damage in Sri Lanka, Nepal, Myanmar, Bangladesh and Pakistan. Substantial amounts of the total yield in field crops can be cached in burrows by these rodents, which are also important storage pests.

Field studies in Bangladesh on the biology and behaviour of the lesser bandicoot rat (*B. bengalensis*), in combination with laboratory results, offered clues for a potential strategy to reduce damage in maturing wheat (Poché *et al.*, 1982). Results from damage surveys showed that wheat fields were not utilized by these rodents until the booting stage, after which rapid immigration, burrow formation and wheat damage were observed. A zinc phosphide bait cake developed in Pakistan (Smythe and Khan, 1980) was effective in small-scale field trials and in a large-scale demonstration in wheat fields. Using this technique, a successful national campaign was carried out in Bangladesh in 1983 and 1984 (Adhikarya and Posamentier, 1987). Despite the minimal cost, time and effort required by Bangladeshi wheat farmers, it is unclear if or how well the programme continued to function. Donor assistance, long ended, played a large initial role in motivating government officials and programme participants. Private industry did not continue the local manufacture of high-quality zinc phosphide bait cakes, thereby permitting other substandard or adulterated products to dominate the marketplace, and probably degrading farmer confidence (Bruggers *et al.*, 1995).

Mathur (1997) found treatments with bromadiolone, warfarin and zinc phosphide baits could control damage by the lesser bandicoot rat in rice, wheat, coconut, and cacao. Singla and Parshad (2010) used bromadiolone alone or zinc phosphide followed by bromadiolone to reduce damage significantly in sugarcane and adjoining wheat fields. An evaluation of an area-wide approach was initiated by Sultana and Jaeger (1992) to determine whether damage in both wet season rice and dry season wheat could be reduced by single rodenticide applications at the time of the year when rodent populations are most vulnerable, after the monsoon floods recede. Preliminary results indicated that this minimal treatment might reduce major crop damage and could be more easily managed by government agencies and farmers.

Arvicanthis niloticus (Nile rat, unstriped grass rat)

The Nile rat (see range map at: http://www.gbif.org/species/2438914) is the predominant rodent pest in field crops in eastern Africa and Egypt and is occasionally abundant in western Africa as well. Nile rats are herbivorous and normally consume grass seeds, leaves and shoots during daylight hours. They have a generally short lifespan; predation may help to limit rodent numbers except during population peaks which, in Senegal, occur about every 4 years (Poulet, 1985). Breeding and population density generally follow seasonal trends related to rainfall and vegetation, including crops (Fiedler, 1988a). During dry seasons, when regional populations decline dramatically, relative abundance may appear to increase as survivors concentrate in restricted areas of irrigated croplands or other suitable habitats and become highly visible to farmers.

Little information has been gathered to describe crop damage from or to develop effective control techniques for this species in agricultural areas. However, it is susceptible to 1% zinc phosphide on whole sorghum bait mixed with 1% vegetable oil (Suliman *et al.*, 1984), a formulation now used in Sudan. Greaves (1989) reported that anticoagulants mixed with wheat grains were effective in the field, but Taylor (1968) observed poor bait acceptance during an outbreak in Kenya, and suggested that natural vegetation may have been preferred over the cereal grain bait being used. Makundi *et al.* (1999) summarized past and current practices for controlling damage by this species and outlined a comprehensive integrated pest management (IPM) strategy for this and associated commensal and agricultural rodents causing preharvest and postharvest losses.

Mastomys spp. (multimammate rats)

These small rodents (see range map at: http://www.gbif.org/species/2438904) are the most important agricultural rodent pest in Africa. The severe crop damage they cause is a result of their omnivorous and opportunistic feeding behaviour, extraordinary reproductive capabilities and a propensity for close association with human settlements. Multimammate rats thrive in the presence of cultivation and readily enter homes, damage stored foods and spread disease.

Considerable effort has reduced, but not eliminated, the confusion in the systematics of *Mastomys* (Robbins and van der Straeten, 1989). Within this species complex, animals display one of three chromosome numbers, which differentiate *M. natalensis* in southern Africa and *M. huberti* in eastern, central and western Africa (both with 32 chromosomes) from *M. coucha* (36 chromosomes) and *M. erythroleucus* (38 chromosomes). All of these types are physically and behaviourally similar, and as pests, they are often treated as one problem.

Although multimammate rats have been involved in virtually every documented regional rodent outbreak in sub-Saharan Africa (Fiedler, 1988b), comparatively little research on the damage they cause or the development of control approaches has been published. Taylor (1968) recorded observations during a major outbreak in Kenya, including an attempt to control the field damage caused by multimammate rats, Nile rats and four-striped grass mice (*Rhabdomys pumilio*). Several other studies that evaluated rodenticide formulations for multimammate rats in the field or laboratory have produced no consensus as to what materials or techniques are suitable for crop damage control (Fiedler, 1988a). Myllymäki (1987) suggested that control efforts should focus on symptomatic treatment during critical damage periods, such as in sown maize or preharvest cotton fields, which would provide Tanzanian farmers with immediate visible results – an approach with a better chance of farmer acceptance.

Like many other African rodents, multimammate rats generally have predictable patterns of breeding and abundance that follow seasonal precipitation patterns (Fiedler, 1988a). Telford (1989) followed *Praomys natalensis* (now *M. natalensis*) population trends and the amount and duration of the two annual rainy seasons occurring in Morogoro, Tanzania, over a 4 year period. Leirs *et al.* (1990) showed that this pattern of bimodal rainfall could be used to predict population densities and potential damage in subsequent crop seasons. These research findings should facilitate the development of an appropriate management strategy for control efforts in Tanzania and other African countries with similar problems (Makundi *et al.*, 1999).

Meriones spp. (jirds)

Damage to field and plantation crops by jirds (see range map at: http://www.gbif.org/species/2437686) is a significant problem in North Africa (Bernard, 1977) and the Near East (Greaves, 1989). Only in India has there been any major effort to examine systematically tropical crop damage problems caused by this group of pests

(Prakash and Mathur, 1988; Mathur, 1997; Parshad, 1999). Damage by *M. hurrianae* populations, which can average ≥300 animals ha^{-1}, occurs in grain and tree crops, grasslands, vegetables and irrigation schemes.

Burrow treatments have been the most practical and useful technique for reducing damage. Only small amounts of bait are required and access to bait by non-target animals is restricted. Whole-grain pearl millet (*Pennisetum typhoides*) is very attractive to jirds, particularly when natural food is scarce. Their hoarding behaviour would probably make multiple-dose anticoagulant baits costly to use except in low-level maintenance control programmes. Nevertheless, the use of chlorophacinone and coumatetralyl, as well as the single-dose anticoagulant brodifacoum, each formulated in a pearl millet base, reduced active burrows by 83, 81, and 91%, respectively, after 10 days (Mathur and Prakash, 1984).

Strychnine (0.5% with mineral oil) and zinc phosphide (0.6–2.5%) on wheat grains have reportedly been successful when used in burrow applications. However, Bernard (1977) reported that tolerance to 0.5% strychnine in some populations required a change in concentration to 2.5% to achieve adequate toxicity. Such strychnine tolerance has also been found in pocket gophers, *Thomomys bottae* (Lee *et al.*, 1990), and large differences in strychnine efficacy have been reported among three subspecies of the California ground squirrel, *Spermophilus beecheyi* (Howard *et al.*, 1990), and in Richardson's ground squirrel, *Spermophilus richardsonii* (Proulx *et al.*, 2010), suggesting the need to check rodenticide efficacy periodically or for use against new species.

Sigmodon spp. (cotton rats)

The distribution of cotton rats (see range map at: http://www.gbif.org/species/2438146) ranges from the southern USA, through Central America, to north-western South America. Although cotton rats occasionally burrow, these 100–200 g herbivorous rodents generally prefer grassy habitats that provide abundant vegetation for shelter, food and nesting. Cotton rats normally are active at night, using distinct runways to traverse a home range of about 0.1–0.5 ha. Breeding can be year round in the tropics, but peaks probably occur in favourable seasons. Population outbreaks occur occasionally over large areas, probably associated with favourable climatic conditions. Holler *et al.* (1981) noted a capability for the doubling of cotton rat populations in 1 month in Florida sugarcane fields. Cotton rats damage maize, sugarcane, rice, cotton and a variety of other field, garden and plantation crops (Espinoza and Rowe, 1979; Elias and Fall, 1988). However, they are less damaging to flooded rice as they remain at the drier edges of fields or along dykes. If populations are high, rapid and significant damage may occur when fields are drained before harvest.

Methods used for controlling damage by cotton rats include removing weeds in and around crop fields to reduce suitable habitat and increase exposure to predation. Rodenticides that are reported effective include the anticoagulants diphacinone (0.005%), brodifacoum (0.005%), pival (0.025%), warfarin (0.025% on maize/groundnut oil), coumatetralyl (0.0375%) and coumachlor (1% in a paraffin/maize meal block). In addition to anticoagulants, zinc phosphide, formulated with grain/vegetable oil or cubed sweet potato, and bromethalin have been used to reduce cotton rat numbers. Lefebvre *et al.* (1978) found that acceptance of 1.88% zinc phosphide formulated on oat groats or cracked maize was similar and that prebaiting did not increase acceptance.

Field evaluations of damage control procedures in Latin America have been very limited. In Mexico, Martinez-Palacios *et al.* (1978) used 0.05% warfarin with a grain-based bait in small bags selectively applied at a rate of 2 kg ha^{-1} over two 1600 ha mixed-crop areas to reduce cotton rat populations at about 50% of the cost of zinc phosphide baiting. They attributed this success to the use of maize oil as an attractant on the bags. Kverno *et al.* (1971) made similar observations in Nicaragua where cotton rat acceptance of non-oiled bags was poor. While rodenticide baiting for cotton rat control still appears to be commonly used by farmers in Latin America, particularly during population outbreaks, no research-based programme recommendations are apparent in the recent literature (Witmer and Singleton, 2010). An extensive summary (in English) of the Latin America rodent research literature had little original information on cotton rat control (Mitchell *et al.*, 1989), and plant protection personnel from the region have had limited participation in recent rodent-control conferences (ICRBM, 2006).

Other important rodent pests of tropical agriculture

Web-footed rats (*Holochilus* spp.) can be important rodent pests in South American sugarcane, rice and cotton (Elias and Fall, 1988; Castillo, 1990). Cartaya and Aguilera (1985) found that most of the damage to rice in Venezuela attributable to *Holochilus* occurred during the earlier vegetative growth stages and amounted to 0.9% of the biomass. These 105–255 g, nocturnal, mostly herbivorous rodents are adapted to aquatic environments, and have partial webbing between the toes on the hind feet. They construct nests and feeding platforms above water level in flooded fields. Anticoagulant rodenticides have been field tested, but only in limited areas and for short periods, using trap success or bait acceptance for evaluation.

Greaves (1989) cast doubt on the frequency of significant crop damage by *Tatera* and *Gerbillus* in the Near East, but elsewhere these gerbils are mentioned as important pests of dryland agriculture (Fiedler, 1988b; Prakash and Mathur, 1988). Govinda Raj and Srihari (1987) identified the reproductive patterns of gerbils (*T. indica*) in India and suggested that control operations should begin before the onset of the breeding season, which is associated with rainfall. Formulated with pearl millet, a preferred bait base, anticoagulant rodenticides reduced active burrows of this gerbil as well as those of a sympatric species, *M. hurrianae*, in crop fields. *Gerbillus* populations occasionally irrupt in Asia and in Africa and are sometimes involved in serious damage to planted seed (Witmer and Singleton, 2010).

Rodent Control, Crop Protection, Integrated Pest Management, Ecologically Based Pest Management and Decision Making

Rodent control describes the approaches used for: protecting crops, natural resources or rare species; preventing the spread of rodent-borne diseases; protecting structures and commodities from damage; reducing overabundant populations in managed areas; eradicating rodents from confined areas such as islands; or removing single individuals from pest situations. Rodent-control programmes are called by many names, some chosen to describe the purpose of the programme, some to describe the methodology, some to conceptualize the general approach, and some simply for purposes of marketing to users, funding agencies or the public. Often, several techniques need to be used in combination to achieve lasting results. Most recently, the processes of selecting management techniques in relation to ecological variables and constraints, applying them in a planned and systematic way, monitoring progress, evaluating results and providing feedback have been termed integrated pest management or IPM (Kogan, 1998) or ecologically based pest management (National Research Council, 1996). Singleton *et al.* (1999a) conceptualized this process as ecologically based rodent management (EBRM).

It is important to recognize that the ecological principles and the array of available techniques involved in all such programmes are similar and that a new name chosen for an effort does not necessarily mean new information or new techniques are being utilized. In the 1994 chapter, we discussed rodent-control programmes in terms of IPM, and we prefer to retain that usage. Smith and Calvert (1978) defined IPM as broad, ecologically based control systems that use and manipulate multiple plant protection tactics in an effective and coordinated way.

More complex definitions have been developed, but theirs remains broadly applicable to all plant pest situations, including those involving rodents. As many countries, international organizations and the donor-supported international agricultural research centres have incorporated IPM into laws, regulations or policies, and established various IPM coordinator positions, we share Kogan's (1998) lament that the invention of new names for a 40-year-old paradigm that has achieved universal recognition, even as an acronym, is non-productive. Minimal field research on the integration of methods and evaluation of programmes has been conducted.

Few practical IPM programmes are in routine use for rodent damage problems in field crops (Spragins, 2006). Smith (1970) recognized more than 40 years ago that chemical pesticides would continue to provide powerful tools in IPM programmes and that the hope for 'revolutionary' approaches to pest control should not be a basis for rejecting effective chemical techniques (e.g. IRRI, 1992). Although IPM, as well as EBRM, has increasingly been promoted as an 'alternative' to use of chemical pesticides, in fact, and in practice, pesticides that are effectively and selectively used remain an important component of most successful IPM programmes, particularly in the management of rodent damage to field crops (Buckle, 1988, 1999). Nonetheless, in every pest situation we have described there are many opportunities to improve the effectiveness, selectivity and environmental compatibility of rodent damage control programmes by developing, evaluating and using ecologically based integrative approaches.

The development of approaches to reduce or prevent crop damage by rodents presents some special problems that require careful consideration (Marsh, 1981; Fall, 1991; Singleton, 1994; Singleton *et al.*, 2003). While the general population dynamics of rodents and the principles for their application in IPM programmes are well known from studies conducted in temperate countries (Davis, 1972), few basic ecological data exist for common rodent pest species in tropical agriculture, though since 1994 the situation has improved substantially, particularly for the most important rodent species. Much of the new literature is well summarized by Singleton *et al.* (1999a, 2003), Stenseth *et al.* (2003), and Witmer and Singleton (2010). The rodent pest species are all highly responsive to changes in environmental conditions, making it essential to develop a thorough understanding of the specific ecological, phenological and climatic factors that influence rodent population behaviour in particular crop situations. This may be particularly important in the future, as climatic patterns change in particular areas. Because rodents may be relatively long lived compared with field crop cycles, have the capability for relatively long-range movements across different habitats, and can reproduce rapidly whenever adequate food and cover are available, most rodent damage problems must be studied and evaluated in farmers' fields rather than on small plots or experiment stations. The same rodents often damage a variety of crops in the same area, shifting from one field to another as crop cover develops or ripening progresses. Seasonal movements from crop fields to dwellings or storage structures are common for a number of problem species. In some cases, more broadly based integrated programmes addressing community problems may be more practical and sustainable than specific crop-oriented approaches (Chapter 14).

Programmes in Malaysia, Indonesia and the Philippines have introduced IPM concepts to rodent control. The sustained baiting method, developed in the Philippines in the early 1970s, contained a self-monitoring component in which bait consumption – a reflection of rodent activity within rice fields – was regularly checked, and the baiting regimen increased or decreased accordingly to minimize rodenticide use (Fall, 1982; Hoque and Sanchez, 2008). Modifications of the procedure using placebo baits have been used for monitoring rodent activity so that control can be initiated when necessary (Howard *et al.*, 1979; Howard, 1983). Based on the Rennison and Buckle (1988) surveillance procedure using rat-damaged rice hills, Buckle *et al.* (1984b, 1985) and Buckle (1988) established thresholds ranging from 15 to 25% damaged hills (equivalent to 1.8–3% cut tillers) for rice field treatment with rodenticides in Malaysia and Indonesia. Recommendations called for weekly baiting with anticoagulants during the rice tillering stage, and the use of tracking powder or fumigation during the maturing stages. Damage assessments at harvest were used to monitor the success of the management programme and identify where rodent control should be emphasized in the next crop season.

IPM programmes that are tailored to the smallest manageable unit that can be handled by a trained farmer or farm worker, with guidance from IPM extension specialists when necessary, probably present the best prospects to be self-sustaining. Such approaches are also more likely to be compatible with other farming and pest-management practices. The sustained baiting technique was designed for a single farmer to use effectively regardless of whether or not surrounding fields were being protected. This approach allowed rodent control to be included in the 'package' of new rice production technology being provided to select Philippine farmers (Fall, 1977). Individual farmer-based programmes place the emphasis on extension workers to provide information to farmers about rodent damage control methods and on market development to assure the availability of materials. Whether using physical control methods or rodenticides, the effects of intensive rodent control on small areas extend well beyond the limits of the individual farm or field, opening up the possibilities of extension strategies that focus on the fraction of progressive farmers most receptive to practising new approaches. In some situations, farm-based programmes may be the preferred approach to manage chronic rodent damage problems, whereas area-wide approaches, directed by specialists, may be appropriate for managing regional rodent population outbreaks, even though both approaches might involve the same crops, rodent species and control methods.

The limited availability of materials for rodent damage control in rural areas is a worldwide problem that must be addressed country by country, and area by area, for the development of self-sustaining and successful IPM programmes. Specific efforts will generally be required by public or private sector organizers, whether the materials needed for a particular programme are rodenticides, bait materials, traps, fencing or simply information. If markets for materials are undeveloped in rural areas, if distribution networks are too costly for the private sector to establish, or if the costs of providing chemical registration or other regulatory data are higher than the potential profit for private industry, then specific government involvement may be necessary. In the USA, the US Department of Agriculture is involved in the development, registration, manufacture and distribution of minor-use vertebrate pest management materials that are needed in IPM programmes for which no other sources are available.

Many of the techniques, materials and practices available for rodent damage control programmes have the potential for adversely affecting other wildlife and reducing biotic diversity. Although farmers cannot be expected to divert agricultural lands or suffer crop damage to maintain wildlife populations, one need only consider the impact of such desperate rodent-control practices as the burning or destroying of habitat adjacent to croplands, or the poisoning of irrigation water, to recognize that the utility and impacts of rodent-control operations need careful evaluation. If other wildlife species are determined to have a measurable role in reducing crop damage, practices to encourage increased activity of predatory mammals or birds around crop fields may be a useful part of an IPM programme. Even if 'natural controls' are not demonstrated as practical components of crop damage prevention, IPM programmes should be developed with the dual objectives of minimizing both crop damage and environmental effects.

An increasing number of countries are requiring that data on wildlife impacts be provided before the use of rodenticides is permitted in field crops. Most rodenticides are toxic to a variety of mammals and some birds, but toxicity data alone are an insufficient basis for regulatory decision making. Because few species of wildlife can live in the transient habitats provided by crop fields, wildlife exposure to rodenticides can often be limited by careful timing of treatments or by selective methods of application. When the costs of evaluating the wildlife impacts of pest management methods and materials outweigh the profitability of potential markets, governments may need to assist in gathering data to ensure that effective IPM programmes can be developed to replace the ineffective, hazardous or destructive practices that farmers may use when nothing else is available.

In any attempt to control crop damage, many small and large decisions must be made by each of the participants. Often, little evaluation of the outcome of these decisions is attempted and practices are simply adopted as routine. Ideally, IPM systems can help to provide feedbacks from the results of rodent damage control operations to those responsible for decision making, ranging from individual producers to government officials. Many constraints – technical, economic, ecological, cultural, religious and political – affect decisions about rodent damage control. It is important to recognize that much of the biological, chemical and ecological information about rodents, rodent damage problems and the effectiveness of techniques and materials has been obtained by researchers without reference to the practical constraints or specific management objectives of any particular crop damage situation. There is a continuing challenge for both producers and pest management specialists to make careful, informed choices in translating the available technical information into safe and effective operational IPM crop protection programmes. However, there is certainly enough biological and technical information about rodent damage control in hand to pursue the development of applied programmes more aggressively (Davis, 1972).

Discussion

Characteristics of successful rodent-control programmes

In 1994, we believed that some initial international support to a tropical country seemed to be prerequisite for progress in rodent control to occur. The Philippines, having one of the more successful national programmes, had major technical and financial assistance from the United Nations Food and Agriculture Organization (FAO), the German Agency for Technical Cooperation (Deutsche Gesellschaft für Technische Zusammenarbeit, or GTZ; now the German Agency for International Cooperation, Deutsche Gesellschaft für Internationale Zusammenarbeit, or GIZ), and the US Agency for International Development (USAID) over a 20 year period (Sumangil, 1991). Other organizations that have provided assistance to tropical rodent-control programmes are the United Nations World Health Organization (WHO), the UK Overseas Development Administration (ODA; now the Department for International Development, or DFID), the Danish International Development Agency (DANIDA), the Belgium Administration for Development Cooperation, the Swiss Directorate of Development Cooperation and Humanitarian Aid, the World Bank, the Asian Development Bank and the Australian Centre for International Agricultural Research (ACIAR). At various times in the past and present, the CGIAR-sponsored international agricultural research centres have actively supported rodent-control training or assistance programmes. Other organizations engaged in rodent-control projects on a smaller scale have included the Rockefeller Foundation, the Bill & Melinda Gates Foundation, CARE, the Catholic Relief Services and the Mennonite Central Committee. Sponsored projects in Asia, Africa, Latin America and the Caribbean have contributed valuable information on key rodent problems.

Clearly, the era of major donor assistance for rodent control to lesser developed countries has ended, and progress in actual control programme implementation on national or international scales has slowed or stopped. Despite this, a number of nationally supported research efforts have emerged, suggesting continuing progress can be expected (Singleton *et al*., 1999a, 2003).

Measuring success

Measuring the success of rodent-control programmes has received little attention. Most managers have had no real obligation or responsibility to evaluate programmes or, if they did, lacked the skills and a budget to do so. In each situation where the application of IPM principles is being considered, specific surveillance and monitoring practices appropriate to the crop, rodent species and farming practices should be devised to provide the essential information about management effectiveness. The common practice of counting dead animals following poisoning programmes gives no indication of programme effectiveness for protecting crops because it ignores remaining or rapidly reinvading animals and provides no information about crop damage.

Two national programmes have been subjected to independent evaluation. Dizon (1978) interviewed managers, extension workers and farmers soon after a new rodent-control programme was introduced in the Philippines and found a substantial lack of knowledge among extension workers and farmers about the required materials and procedures. Despite this handicap, about 2% of farmers after 1 year and about 12% after 2 years had adopted all or portions of the new technique. The management information system developed and used by the Philippine Bureau of Plant Industry to track rodent-control efforts in relation to crop damage assessments (Sumangil, 1991) provided a mechanism to maintain a national overview during the initial efforts to implement new procedures for rodent damage control (Hoque and Sanchez, 2008; Singleton *et al*., 2008).

Adhikarya and Posamentier (1987) evaluated rodent-control campaigns in Bangladesh, where considerable effort was expended on developing and testing extension methods designed to motivate farmers. As a result, an additional 5045 t of wheat were harvested in 1983, and in 1984 an additional 5208 t of wheat were realized. Bait costs for these campaigns averaged about 3–5% of the value of the increased production. The gains were probably larger because only wheat fields were evaluated, even though non-wheat crops were officially included in the 1984 campaign.

In addition, a number of countries with some tropical agricultural areas within their borders have engaged in both rodent research and control efforts. India, in particular, with diverse rodent damage problems across several climatic zones (Prakash, 1988; Parshad, 1999), has long maintained science-based, nationally coordinated rodent-control programmes with reporting and evaluation components.

Keys to success

Ecological understanding of crop damage problems

The full understanding of a rodent pest problem requires considerable time for studying rodent biology and behaviour under actual field conditions (Singleton *et al*., 1999a). Beyond this important initial research phase, the monitoring of rodent reproduction and movements, population status and condition, and crop damage patterns, and relating these data to climate and vegetation over several seasons, can provide the basis for models to forecast with reasonable accuracy short- and long-term rodent population and changes in damage (Leirs *et al*., 1996; Stenseth *et al*., 2001). With appropriate quantitative techniques, sensitivity testing on individual components of a model can identify key factors contributing to crop damage and help to identify appropriate control strategies and methods for field evaluation (Benigno *et al*., 1983).

Establishment of clear programme objectives

A control programme should have stated objectives that focus on effectively reducing damage to priority crops and increasing farm yields and income within a given area and period. In many cases, an 'area' can be an individual farm. With such a focus, a programme will be less likely to lose sight of its primary mission. Successful programmes have made extensive and creative efforts to inform farmers and rural populations about the purpose and potential benefits of effective rodent damage control.

Well-organized implementation efforts

A well-organized operational programme can reduce significant rodent damage. During the 1976 rodent outbreak in Sudan, all areas of the country (including the Gezira Scheme, an intensively irrigated agricultural production area of more than 930,000 ha located between the Blue and White Nile Rivers) were severely affected by rodent damage. A result of this outbreak was the establishment of a programme in the Gezira Scheme to research, conduct and monitor operational rodent control. Some 10 years later, during the 1986–1987 Sudan rodent outbreak, the only area in the country not seriously affected was within the Gezira Scheme, where the well-organized rodent-control programme had been continued. Not only were annual yields protected from chronic losses over several years, but severe damage during one of Sudan's worst rodent outbreaks was avoided (Fiedler, 1988a).

In too many situations, there is no organization until an outbreak or some other acute problem requires it. Hastily made decisions are then usually based on limited, earlier research or information from other situations, which may or may not apply (Ramsey and Wilson, 2000). Responsibilities for specific actions must be recognized from the highest levels of government to the individual farmer, or control programmes will be ineffective. For example, at national levels, health and agriculture officials may not agree on who is responsible for rodent control when both public health and agricultural production are at risk from overabundant rodent populations. At the farm level, farmers may delay action because they feel that the government will take responsibility for controlling rodents.

Providing technical information to programme participants

An informed public is more cooperative and more likely to participate in rodent damage control programmes (Rampaud and Richards, 1988), but questions remain about how to inform. In this sense, the problems of improving rodent damage control parallel those of other agricultural production technologies. Effective communication methods will vary with social and cultural traditions, which can pose some formidable constraints in rodent-control technology transfer. For example, Adhikarya and Posamentier (1987) tested various Bangladeshi extension materials for farmer acceptance and found that some symbols and pictures in those extension materials had to be eliminated or changed because of adverse meanings or implications previously unknown to them. IRRI in the Philippines developed various production and pest management guides (for example, Reissig *et al.*, 1985) and has periodically sponsored workshops and training sessions for farmers, extension technicians and research workers. Elsewhere, radio broadcasts have been used to inform farmers, and widely distributed posters have been used in control campaigns introducing new national programmes. The introduction of rodent-control information through schools and local markets, training sessions involving key farmers or farmer groups, and the selection of demonstration farms, are other approaches that may have value in some situations.

Reasons for slow progress

Sustained adoption of improved rodent damage control methods, even those that have been properly researched, developed, demonstrated and extended to farmers, has been low, although we believe substantial improvement has taken place since we studied the problem in 1994. Poor adoption is frequently blamed on costs of materials, limitations on labour, the unpredictable nature of crop damage, or the lack of information and appropriate materials at appropriate times in crop cycles. Subsistence farmers may have little incentive to control rodents or to increase crop yields until land is predictably available or markets for crops are developed. Without some type of credit programme, even progressive farmers may lack the money required for preharvest investments in crop protection materials, or they may be reluctant to borrow even when credit is available, sometimes because of a history of excessive or unpredictable losses of crops to pests, weather or other factors.

For the most part, farmers rely on their own experience and that of their neighbours in making decisions on adopting new technology. Substantial benefits in farmers' fields create awareness, but, as many programmes have learned, creating awareness is much easier to accomplish than motivating farmers to use new technology. Of course, from the farmer's standpoint, rodent damage is only one of many risk factors that can result in crop losses; similarly, crop protection is only one of many aspects of crop production that a farmer must manage (and finance) year after year. In many tropical agricultural situations, a conservative attitude by farmers in the adoption of and investment in new technology is to be expected. This expectation should be a part of programme development and planning.

Poor programme results can also be expected if the involvement of government and rapport with farmers are lacking. However, the involvement of governments should not result in farmer dependence, which can be a major hindrance to establishing rodent damage control as an ongoing crop protection effort. The time and effort involved in organizing and managing effective government rodent-control programmes is much more than most realize. A national programme in Taiwan took 6 months to prepare and 2 months to evaluate in addition to the actual control operation (Ku, 1984). The marketing of ineffective or adulterated rodent-control products (Bruggers *et al.*, 1995) may result in farmers avoiding the further use of similar materials, good or bad. Government involvement in the quality assurance and regulation of agricultural chemicals may help to prevent this lack of farmer confidence. Sometimes, the non-availability of, or lack of easy access to, markets for excess produce inhibit farmer efforts and investments to increase crop production. Increasing national crop yields may prove to take decades of change – in social attitudes, agricultural policies, farmer awareness and knowledge, and development of the necessary infrastructure and support systems in rural areas. Continued effort is needed to ensure that the development of technology and programmes for controlling rodent damage is coordinated and keeps pace with other efforts in agricultural development.

The need for dynamic rodent damage control programmes

International agency support for research, training, operations and coordination was an initial driving force in the development of many national programmes. The publication of the results of research and development activities related to rodent control has made much valuable information readily available, including crop damage estimates for several important rodent species (Witmer and Singleton, 2010). National priorities are influenced mostly by economic factors, and without convincing descriptions of the extent of losses, rodent control will be likely to remain a low priority (Richards, 1988). Programmes that have had more success than others have identified economic losses and used the results either to initiate other programmes or strengthen existing ones.

In many surveys, farmers in the tropics rank rodents among their most significant crop pests (for example: Litsinger *et al.*, 1982; Adesina *et al.*, 1994; Singleton *et al.*, 1999b; Tuan *et al.*, 2003; Makundi *et al.*, 2005). This view is often endorsed by government plant protection officials. However, vertebrate pests have more often been viewed either as too different to be considered in insect-oriented national crop protection programmes or, indeed, as unique and so also not suitable for consideration in such programmes. Rarely have rodent damage management programmes been included with other IPM efforts. National crop production/protection packages and recommendations could easily incorporate available information on rodent-control technology, thus allowing the strategies to achieve technology adoption to be developed and implemented in a coordinated manner so as to provide comprehensive information to farmers. We believe considerable progress has been made in this regard since we first began to investigate tropical rodent problems in the 1960s.

Rodent pest management is not a temporary problem. Changes in agricultural habitats, the introduction of new crop varieties and farming practices, the development of improved irrigation, greater annual crop production, the continued rapid growth of human populations and changing climatic patterns will all cause many ecological changes that affect rodent behaviour, population patterns and crop damage. If control methods and management programmes are dynamic enough to account for these changes, the successes achieved so far will be sustained and progress in rodent damage control can continue (Witmer and Singleton, 2010).

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