Control of rodent pests in rice cultivation

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1 Introduction

Rodents remain one of the main nuisances to mankind. For thousands of years they have been causing damage to crops, stored grain and infrastructure, and are reservoirs for devastating human diseases such as plague and typhus. The bones of rats and mice are found along with human bones from the mid-Pleistocene (1–2.5 million years ago). Rats and mice subsequently radiated throughout the world. Rodents continue to cause serious damage to staple food crops such as rice (John 2014), despite advances in methods of control and management techniques.

The order Rodentia is one of the most widely distributed order of animals throughout the world. There are more than 2700 rodent species described, and the Rodentia order accounts for 42% of all mammal species (Aplin et al. 2003; Macdonald 2001). They are primarily seed eaters, but some are insectivorous and some are omnivorous. The success of the pest rodent species can be attributed to their short lifespan, high rates of fecundity (high litter sizes, short gestation period and short duration to sexual maturity), potential to disperse long distances, complex social hierarchy, flexible social systems and their

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physiology and body structure which allow them to live in a wide range of environments (Prakash 1988; Buckle and Smith 2015). There are five broad suborders of rodents based largely on their jaw structure and gnawing phenology and function: Anomaluromorpha (scaly tailed squirrels, springhares), Castorimorpha (beavers, pocket gophers, kangaroo rats), Hystricomorpha (African mole rats, porcupines, cane rats, chinchilla rats, cavies, guinea pigs, capybara, agoutis, nutria, coypu), Myomorpha (jerboas, muskrats, voles, lemmings, true mice and rats, spiny dormice, mole rats, bamboo rats) and Sciuromorpha (mountain beaver, dormice, squirrels, chipmunks, prairie dogs, marmots).

In some cultures, rodents are held in high regard: In China and Japan, the clever and quick-witted rat is considered a symbol of good luck and wealth. It is the first animal in the Chinese Zodiac. In Vietnam, rodent meat is eaten to bestow good fortune and fertility on the newly-weds. In Myanmar, the rat is one of eight calendar figures – people born on a Thursday carry the rat as their figure and Buddhists visit pagodas to worship their birth figure. In India, there are a few temples where the local rat species is not allowed to be harmed, and people freely feed and provide milk for them. In general, however, rodents are held in poor esteem and considered major pests because of their devastating impacts. However, less than 10% of the species belonging to the Rodentia order are significant agricultural pests; the others generally play an important beneficial role in the ecosystem (Singleton et al. 2007).

Rodents are among the world's most important pests (Prakash 1988; Singleton et al. 1999a; Buckle and Smith 2015), causing significant damage to agricultural production throughout the world (Elias and Fall 1988; Hoque et al. 1988; Lund 1988; Marsh 1988; Fiedler 1994; Singleton 2003; Singleton et al. 2010a). It has been estimated that less than 10% of rodent species are major pest species of agricultural and urban areas (Stenseth et al. 2003; Singleton et al. 2007); however, it is in the poorer developing countries that the impact of rodents is generally greatest. In Indonesia, rodents are considered the most important pre-harvest pest of rice, causing around 15% losses annually (Geddes 1992); and, in Tanzania, rodents cause an estimated 5–15% loss of maize (Leirs 2003). Farmers report yield losses of between 0 and 100%, with occasional outbreaks devastating on smallholder farmers (Singleton et al. 2010b; John 2014). Surveys of rice farmers have revealed that rodents are considered the most important constraint for rice production for 98% of farmers, and have been described as the pest they have least control over (Schiller et al. 1999).

Rodents also cause problems through disease transfer to humans and to their livestock. Rodents are the carriers of human diseases (rodent-borne zoonoses) such as the plague, rat-borne typhus, hantavirus diseases and arenavirus infections (Mills 1999; Meerburg et al. 2009a). Rodents carried parasites that were responsible for the Black Death (*Yersinia pestis*), which killed 20 million people from 1347 to 1350 (between 30 and 50% of Europe's population) (Cantor 2001). Rodents also transmit leptospirosis, a disease with a global distribution that has had major impacts in Indonesia, Thailand, Vietnam, Australia and the Pacific Islands in recent years (e.g. Tangkanakul et al. 2005; Tubiana et al. 2013). In developing countries, mortality rates range from 2 to 10% of those infected, but it is easily treated with antibiotics if diagnosed early. The disease affects many rural communities, especially in developing countries and is often misdiagnosed as malaria or dengue fever (because of the influenza-like symptoms). Most farmers come in contact with the spirochaetes of leptospirosis as they work in their fields. In 2000, there were 14 285 cases of leptospirosis with 362 deaths reported in Thailand (Tangkanakul et al. 2005).

Much is known about the biology, genetics and behaviour of rodents, especially through studies of the laboratory rat (*Rattus norvegicus*) and the laboratory mouse (*Mus domesticus*).

Laboratory mice have advanced our understanding of genetics and reaction systems for mammals and they provide an important model for disease and for drug design and monitoring (Berry and Scriven 2005). Despite this understanding, we are, comparatively, on a fast-learning curve about how wild rodents interact with their environment. More knowledge is required, particularly on rodents that cause damage to rice crops.

Given the important role of rice production in global food security, it is important to manage rodent damage to rice. It is therefore necessary to understand the ecology of the pest species and the nature of the damage they cause, leading to the development of appropriate methods to minimise the damage caused. Rodent management is primarily about controlling damage caused (therefore reducing losses to farmer's rice yield), not killing rodents *per se*.

2 Rodent impacts on rice

2.1 Pre-harvest losses from rodents

Rodents may damage rice at all stages, from sowing through to ripening and harvest. After sowing, rodents can consume the entire seed or seedling, which leads to the complete removal of a plant. Once tillers have emerged, rodents generally bite off the tillers near the base, but provided there is sufficient plant remaining, it is possible for the plant to compensate for that damage by producing new tillers or regrowing cut tillers. However, following the maximum tillering stage, there will be a yield penalty – the later the damage, the greater the yield penalty (Buckle et al. 1979; Buckle 2015; My Phung et al. 2010). From mid-tillering, rodents cause damage to rice by cutting at an oblique angle near the base of tillers. Rice is most susceptible to rodent damage from the booting (reproductive) stage to harvest.

It is notoriously difficult to assess rodent damage and losses to rice at a crop and landscape scale because damage is typically patchy (e.g. Buckle 2015; Miller et al. 2008). Measurements can be made of the number of rodent-cut tillers on rice plants, but this may not necessarily translate into yield losses. Rodent damage might be easy to see, but vegetative recovery can mask the appearance of damage at harvest (Wood and Singleton 2015). Farmer estimates are subjective and can be wildly inaccurate. Farmers often do not notice damage until it is greater than 5–10%.

The nature of rodent damage to rice can vary, depending on the species of rodent and the type of rice grown. There is no consistent pattern of damage and losses due to rodents in different rice systems in different countries (Table 1). Some species, such as *Bandicota bengalensis*, cut tillers and hoard them in their burrows (see Htwe et al. 2017). Other species feed in the field. Some species eat in small areas and cause localised patches of damage. When abundance is high, some species, in particular *R. argentiventer* and *R. tanezumi*, cause damage towards the centre of fields, away from the field edge. This pattern of damage is known as the 'stadium effect' (Benigno 1980).

There have been a range of methods used to assess rodent damage to rice crops. These include diagonal transects (Rennison 1979), random quadrat sampling (e.g. Salvioni 1991) and parallel transects from the edge of the crop to halfway into a field with sampling points at right angles to set distances from the edge (Aplin et al. 2003; Singleton et al. 2005). The latter method is designed to capture the spatial variation of rodent damage, particularly given there is more damage to rice tillers towards the centre of a field. Miller et al. (2008) were able

Table 1 The twenty largest rice-producing countries in the world and the corresponding pest species of rodents. Rice statistics from 2015 (IRRI rice statistics: http://ricestat.irri.org:8080/wrs2/entrypoint.htm). There is a lack of information on rodent pests in rice for some countries

Country	Rice system	Rice area (000 ha)	Rice production (000 tonnes)	Main rodent species	Estimated losses	Nature of losses	Reference
China	Irrigated lowland	30,210	208,243	*Rattus nitidus*, *Rattus turkestanicus*, *Bandicota indica*, *Rattus losea*, *Rattus rattus* complex, *Microtus fortis*, *Rattus rattoides*, *Rattus norvegicus*, *Mus musculus*, *Apodemus agrarius*	5–10%	Severe, varies between years	Deng & Wang (1984), Zhang et al. (1999), Wood & Singleton (2015), Zhao (1996), Singleton (2003)
India	Irrigated lowland	43,000	150,015	*Nesokia indica*, *Mus booduga*, *Bandicota bengalensis*, *Millardia meltada*, *Bandicota indica*, *Rattus nitidus*, *Rattus meltada*	5–15%	Some outbreaks associated with bamboo masting	Sridhara (1992), Wood & Singleton (2015), Barnett & Prakash (1976), Singh et al. (1994), Parshad (1999)
Indonesia	Irrigated lowland	12,160	57,165	*Rattus argentiventer*	10–17% in Java	Chronic and occasional outbreaks associated with weather events	Singleton (2003), Singleton et al. (2005), Sudarmaji et al. (2010)
Bangladesh	Irrigated and rainfed lowlands	12,000	51,905	*Rattus rattus* complex, *Bandicota bengalensis*, *Bandicota savilei*, *Bandicota indica*	5–10% (>50% in some districts)	Some outbreaks associated with bamboo masting	Aplin et al. (2003), Islam et al. (1993), Singleton (2003), Belmain et al. (2015)
Vietnam	Irrigated lowland	7,660	45,120	*Rattus argentiventer*, *Rattus sakaratensis* (formerly considered *R. losea*), *Rattus rattus* complex	5–30%	100,000 to 700,000 ha with high annual damage (>10%); outbreaks due to unusual rainfall events	Brown et al. (2005), Singleton (2003), Huan (2010)
Thailand	Rainfed and irrigated lowlands	9,650	24,848	*Rattus argentiventer*, *Rattus sakaratensis* (formerly considered *R. losea*), *Rattus rattus* complex, *Bandicota indica*, *Bandicota savilei*, *Rattus exulans*, *Mus caroli*, *Mus cervicolor*	1–18%	Highest in central region; varies markedly between years	Boonsong et al. (1999), Singleton (2003)

Myanmar	Irrigated and rain-fed lowlands	6,800	19,063	*Rattus rattus* complex, *Bandicota bengalensis, Bandicota savilei*	5–40%	Some outbreaks associated with bamboo masting or extreme weather events	Aplin et al. (2003), Singleton (2003) Htwe et al. (2013)
The Philippines	Irrigated lowland, upland	4,650	18,254	*Rattus tanezumi, Rattus argentiventer, Rattus norvegicus, Rattus exulans*	District losses 10–20%	Variable, some outbreaks	Fall (1977), Singleton (2003), Singleton et al. (2008); Stuart et al. (2011)
Brazil	Irrigated lowland	2,300	11,765	*Holochilus brasiliensis, Sigmodon hispidus*		Some outbreaks associated with bamboo masting	
Japan	Irrigated lowland	1,610	10,852	Insufficient information			No recent published studies
Pakistan	Irrigated lowland	2,850	10,351	*Nesokia indica, Bandicota bengalensis, Millardia meltada, Mus* spp.	10–25% damage, 2–43% loss (mean 19%)		Wood & Singleton (2015), Fulk & Akhtar (1981)
The United States of America	Irrigated lowland	1,042	8,724	Insufficient information			No recent published studies
Cambodia	Rainfed lowland, upland, irrigated lowland	2,900	6,797	*Rattus argentiventer, Bandicota indica, Rattus exulans, Rattus rattus* complex	Patchy	No national data	Aplin et al. (2003), Singleton (2003)
Egypt	Irrigated lowland	800	5,797	*Arvicanthis niloticus*			No recent published studies
South Korea	Irrigated lowland	799	5,771	Insufficient information			No recent published studies
Sri Lanka	Irrigated lowland	1,225	4,853	*Bandicota bengalensis, Rattus rattus* complex, *Mus cervicolor*	?	?	Bambaradeniya et al. (2004)
Nepal	Irrigated lowland	1,560	4,655	Insufficient information			No recent published studies
Nigeria	Rainfed lowland	2,400	4,300	*Arvicanthus niloticus, Dasymys incomtus, Tatera kempii, Mastomys natalensis, Lemniscomys striatus, Uranomys foxi, Rattus rattus, Mus musculoides*	4.8–12.6%		Rabiu & Rose (2004), Funmilayo & Akande (1977), Wood & Singleton (2015),
Madagascar	Irrigated lowland, rainfed lowland	1,450	3,700	*Rattus rattus*	2.5% yield loss	86% of farmers report rodents as important pests	Duplantier (1999)
Peru	Irrigated lowland	400	3,120	Insufficient information			No recent published studies

to better capture this spatial variation in rice terraces by estimating areas of low, medium and high rodent damage and then using stratified random assessment of rodent damage.

Rodents are significant pests in all rice cropping systems: irrigated lowland, rainfed lowland, upland rainfed and deep water/tidal wetlands (Singleton 2003; Table 1). In Vietnam, the rodent problem escalated in the 1990s in the Mekong and Red River deltas due to an increase in cropping intensity; two and three rice crops were grown annually where previously only one or two crops were grown (Lan et al. 2003). In Indonesia (Singleton et al. 2003a), Malaysia (Lam 1988), Myanmar (Htwe et al. 2013) and Vietnam (Huan et al. 2010), asynchrony of cropping was reported as a major driver of high losses to rodents. We propose that regardless of the rice agro-ecosystem, there is likely to be a relationship between the level of losses to rodents and both the intensity of cropping and the level of asynchrony of cropping. Intensive lowland irrigated rice is the most intensive cropping system and therefore suffers the highest losses to rodents due to an extended period of increased availability of food that results in rats breeding more often during a year, and for longer when there is asynchronous cropping (Singleton et al. 2010b).

It is important to understand economic thresholds for rodents and yield losses. Much work has been done on insects in rice (see chapter 12 of this volume), but there are only a few examples of this for rodents in rice, and these have been achieved mainly through simulation modelling (Brown et al. 2011; My Phung et al. 2010; Mulungu et al. 2014a).

2.2 Post-harvest losses from rodents

Rodent losses to stored rice have been claimed to be higher than rodent pre-harvest losses in South Asia (Parshard 1999). The numbers of studies of rodent post-harvest losses, however, are few. Recent publications have documented losses at 4–14% in Myanmar (Belmain et al. 2015; Htwe et al. 2017), 10% in Laos (Brown et al. 2013) and 3% in Bangladesh (Belmain et al. 2015). The losses by rodents depend on the species composition, storage structures, sanitation around storage areas and the duration of storage. The dominant species in stored grain were those of the *R. rattus* complex in Laos; *R. rattus*, *R. exulans* and *B. bengalensis* in Myanmar; and *Mus musculus* in Bangladesh. Interestingly, the main pest species to grain stores are often different from those that cause losses in the field with perhaps the exception of Myanmar (Htwe et al. 2017), indicating that often we cannot apply our understanding of the breeding dynamics and spacing behaviour of field rodent species to those that live in and around houses and grain stores.

3 Rodent pests of rice and their biology

There are many species of rodents that cause damage to rice. Some have global distributions (e.g. *R. rattus* complex; Aplin et al. 2011), some have wide distributions across much of Southeast Asia (e.g. *R. argentiventer* and *R. sakaratensis* (formerly considered *R. losea*)) and in sub-Saharan Africa, for example *Mastomys natalensis* (Leirs et al. 1994; Mulungu et al. 2011), and still others are found in a relatively more limited range. Some regions have only one or two species, while others can have relatively large rodent communities (e.g. Mekong Delta, Vietnam, with up to ten different species) (Aplin et al. 2003). A summary of the pest rodent species present in the main rice-producing countries is shown in Table 1 and a summary of the nature of the impact is shown in Table 2.

Table 2 Level of threat posed by selected rodents to rice crops. Key: + = low threat, ++ = moderate threat, +++ = high threat,? = lack of direct evidence. Source: Aplin et al. (2003). There is incomplete knowledge about the rodent species in Brazil, Cambodia, Egypt, Japan, Madagascar, Nepal, Nigeria, Peru, South Korea, Sri Lanka and the United States

Species	Removal of seeds	Removal of emerging plants	Cutting of tillers	Removal of maturing grain	Remarks
Bandicota bengalensis	++	++	++	++	Breeding linked to crop stage, damages all stages, causes most damage near burrows, hoards grain (1.7 kg of rice grain/burrow system)
Bandicota indica	+	+	++	++	Breeding not linked to crop stage, only causes damage at moderate to high densities, hoards grain
Bandicota savilei	?	?	?	?	Can be locally abundant and prefers lowland rainfed rice with no widespread flooding
Cannomys badius	?	?	?	?	Causes some damage to upland rice crops in Laos, tunnels below rice plants and consumes plants from below
Mastomys natalensis	+++	+++	++	++	Breeding is throughout the year but most female individuals are active during the crop maturity stage, damages all stages (Mulungu at al. 2013, 2015a)
Mus booduga/terricolor	+?	+?	+?	+?	Can breed all months of the year, can cause damage at any crop stage
Mus caroli/cervicolor	?	?	?	?	Common in rice fields, very agile and climb plants to damage developing seeds
Mus cookii	?	?	?	?	Often captured in and around rice fields, but little is known of its impact
Mus musculus	+	+	+	+	Breeding linked to season, damage at all stages, but *Mus* spp. often makes up a small proportion of rodent community
Nesokia indica	?	?	+	+++	Can cause extensive damage to rice and other crops, in Pakistan it consumes only ripening grain
Rattus argentiventer	++	++	+++	+++	Key pest in Southeast Asia causing heavy damage at high densities. Breeding linked to crop stage
Rattus exulans	+	+	++	++	Usually confined to houses and villages, but can cause some damage to crops
Rattus losea/sakaratensis	++	++	++	++	Breeding linked to crop stage, competes with *R. argentiventer* in most of ranges
Rattus nitidus	?	?	?	?	China (Sichuan Province) and Thailand, breeding linked to crop stage
Rattus norvegicus	+	+	+	+	Mainly pest in urban areas, with scattered populations in Thailand, Vietnam and the Philippines, damage not recorded
Rattus rattus complex	++	++	+++	+++	Found in village, urban, crop fields and forests, competes with other species, damage only around the edge of fields, breeding linked to crop stage
Rattus tanezumi	++	++	+++	+++	Found in village, urban, crop fields and forests, damage often concentrated in the centre of rice fields, can breed throughout the year but peaks in breeding linked to crop stage
Rattus turkestanicus	?	?	?	?	Breeding linked to maturing rice in Fujian Province and Xiamen Province (China), damage to early ripening rice crops

The breeding dynamics of some rodent species is linked to the crop stage of rice (Table 2), for example, *R. argentiventer* (My Phung et al. 2011). It has a natural preference for waterlogged areas with grassy habitat, making it ideally suited to rice fields (Aplin et al. 2003). If there is one rice crop per year, *R. argentiventer* will breed once a year. If there are two rice crops per year, they have two breeding seasons. Three breeding seasons are apparent when there are three rice crops per year. *R. argentiventer* commences breeding at maximum tillering stage and continues through to harvest. If the rice crops are not synchronised and the breeding season is extended, then the young from the first litter will be mature enough to breed themselves, thus resulting in an exponential increase in abundance (Leung et al. 1999).

A similar association between rice crop growth and breeding activity is apparent for *R. tanezumi* in the Philippines and *M. natalensis* in Tanzania. However, these species are able to continue breeding at low levels (10–20% adult females breeding) at times when no ripening rice is available (Duque et al. 2008; Htwe et al. 2012; Mulungu et al. 2013; Stuart et al. 2015).

Pest rodent populations have the ability to grow rapidly in response to good environmental conditions or following lethal control because they have high rates of reproduction (many offspring, short gestation period) and/or survival (high growth rates, *r*-selected species; with boom and bust characteristics), compared to species at carrying capacity (slow growth rates, *K*-selected species) (Hein and Jacob 2015). Pest rodents can either be native to a particular area or introduced by humans. Most reach sexual maturity at 2–3 months of age, with the females producing 6–7 young after a gestation period of only 2–3 weeks. Females are also capable of post-partum oestrus, meaning they can become pregnant straight after giving birth to a litter of young, thus allowing another litter to be produced when one litter is weaned.

In intensive lowland-irrigated rice cropping systems, rodents cause chronic losses, although the amplitude will vary from year to year. Probably of greater economic concern for smallholder farmers are the episodic outbreaks that can lead to losses of 50–100% of the rice crop. There have been three types of outbreaks described for rodents in rice cropping systems (see Singleton et al. 2010a for review):

1 Masting events (e.g. bamboo and beech trees) not related to climate or farming systems,
2 Changes in abiotic conditions alone (aseasonal or unusual rainfall event, or major climatic events such as El Niño) that create episodic rodent population outbreaks in response to increases in food availability, and
3 Changes in cropping systems: anthropogenic responses to calamitous events such as typhoons, cyclones and droughts. Anthropogenic responses include delayed or asynchronous planting or increased intensity of cropping.

Rodents build nests in and around rice fields or surrounding vegetation, non-rice habitats or houses/village habitats. In irrigated lowland rice monocultures of the Philippines, female *R. tanezumi* nest along the edges of rice fields and within ripening fields, between the rice tillers (Fall 1977). Whereas, in complex agroecosystems, female *R. tanezumi* predominantly nest in adjacent coconut groves, including within the crowns of coconut trees (Stuart et al. 2012).

A number of studies on the movement and habitat use, relating to changes in the abundance of *R. argentiventer*, have been conducted and show that habitat use of *R. argentiventer* was responsive to rice crop growth stage, rice plant cover (Brown et al. 2001; My Phung et al. 2012) and patches of high-quality habitat (Jacob and Wegner 2005). The movement of *R. argentiventer* is greater in the non-breeding seasons than in breeding seasons, with males travelling further than females in the breeding seasons (Brown et al. 2001). Not enough studies of other species in rice systems have been conducted to draw generalities.

In rice fields, an established population of *R. tanezumi* is restricted to a home range of around 100 m (Alfonso et al. 1985). However, the home range changes at different stages of the rice crop (Singleton et al. unpublished data); just before and after rice harvest, the average home range of *R. tanezumi* individuals was found to be 0.6 ha for males and 0.3 ha for females. During the milky-ripe stage of the rice crop, males had an average home range of 1.8 ha and females had an average home range of 0.8 ha.

Knowledge of foraging behaviour and food preferences is vital to the successful use of rodenticides. Baits placed within rice fields are likely to be more attractive and more readily accepted during the tillering stage of the rice crop because food availability is low and pest rodents move into the rice field from the surrounding habitats during this time (Stuart et al. 2015). When rice plants enter the reproductive stage, the acceptability of rodenticide bait is expected to decline and will be less effective (Buckle and Rowe 1981).

Generally, rodent pest species are considered to be opportunistic omnivores with a dominant component of their diet comprising seed (Bomford 1987), insects (Berry and Bronson 1992; King et al. 1996), crabs, snails (Tann et al. 1991) and macadamia nuts (Horskins et al. 1998). The dietary preference of *R. argentiventer* was mainly rice, followed by green material, insects and mung bean (My Phung et al. 2011).

In a rice field ecosystem of the Philippines, rice has been identified as the main component of the *R. tanezumi* diet during the ripening to harvest stages of the rice crop (Tigner 1972; Htwe et al. 2014). Insects, weeds (e.g. *Digitaria* sp., *Ipomoea aquatica* and *Echinochloa colonum*), snails and crabs have been identified as the dominant food items during the off-season months when rice grains were absent. Other foods included grasses and other vegetative matter (Htwe et al. 2014). *R. tanezumi* also feed on agricultural crops other than rice, such as coconut, maize and banana.

4 Rodent management methods

There are a wide range of management options available that can be used to control rodents in rice systems. These are largely designed to kill animals, but there are a few exceptions (e.g. habitat management and biocontrol; detailed below). These methods can be categorised as physical, chemical, biocontrol and others. The ultimate aim of a rodent management programme is to reduce the impact (e.g. reduce rat damage to rice), not kill animals *per se*. The advantages and disadvantages of each management method are presented in Table 3. Farmers often attempt to control rodents when they see damage, which is often too late because rodent population numbers are already high, so a good understanding of the timing of control for the maximum benefit of reducing rice yield loss is necessary (see Section 4.5 for details).

Table 3 Advantages and disadvantages of different control strategies to manage rodents in rice-based cropping systems

Method	Advantages	Disadvantages
Trapping – snap traps	• Easy to set	• Can only kill one animal at a time • Useful in small-scale situations • Not effective when abundance of rodents high • Unwanted non-target effects
Trapping – live-traps	• Easy to set	• Small number of animals captured • Need to kill captured animals
Barriers – plastic fence	• Protects small areas of crop, for example, rice nurseries	• Takes time and effort to set up • Plastic only lasts 1 or 2 seasons
Barriers – trap-barrier system (TBS)	• Can capture a large number of rats • Can protect large areas of rice (10–15 ha)	• Takes time and effort to set up • Needs to be planted 2–3 weeks earlier than surrounding fields • Needs a community-based approach for best results
Habitat management	• Increases predation risk	• Needs to be applied at the right time • Takes effort to apply herbicides or slashing • Conflict with conservation
Crop synchronisation	• Reduces length of rat breeding season	• Needs coordination among neighbouring farmers (>100 ha)
Bund size	• Reduces rodent burrows	• May not be appropriate in all situations
Rodenticide – acute	• Easy to apply • See dead rodents • Immediate effect	• Unwanted non-target effects • Often no antidote available • Bait shyness
Rodenticide anticoagulant	• Easy to apply • Antidote available • No learnt bait shyness	• Takes longer for effect • Can be expensive • Unwanted non-target effects
Fumigation	• Relatively easy to apply	• Need to locate all burrows to be effective • Takes a lot of labour to do properly
Repellents	• Limited non-target effect	• No strong evidence for lasting effect
Sterility control	• None known	• Bait delivery difficult
Reproductive inhibitors	• None known	• Bait delivery difficult
Predators	• Relatively cheap	• No definitive proof that predators increase rice yields
Parasites and diseases	• Reduce reliance on chemical rodenticide	• Limited availability of commercial products
Diversionary feeding	• Cheap	• No evidence it works in rice fields
Hunting	• Can be conducted at any time • Large numbers can be killed when hunting as a group • Source habitats can be targeted	• Group hunting takes time and effort to organise
Electricity	• No advantages	• Highly dangerous
Ultrasound/ electromagnetic devices	• No advantages	• Not effective
Ecologically based rodent management (EBRM)	• Positive benefit:cost ratios	• Requires coordination at community scale

4.1 Physical rodent management methods

4.1.1 Trapping

Trapping is a widespread and common tool for removing rodents. There are many 'village industries' based around the construction and sales of local rat traps. These include wire traps in the uplands of Laos and bamboo traps in Myanmar. Kill traps are generally spring loaded and are designed to rapidly compress the cervical vertebrae for a very quick kill. These traps need to be either attractive to rats via the placement of an attractive bait or are set along runways. The effectiveness of physical trapping depends on the behaviour of the species. For example, the house mice (*M. musculus*) are more likely to be trapped because they are relatively neophilic, whereas some species are notoriously difficult to trap, for example, black rats (*R. rattus*) and Norway rats (*R. norvegicus*) because they are relatively neophobic. Therefore, a pre-baiting strategy may be required to leave the traps unset for 3–5 days before setting, and a good bait is often needed to make traps effective. Other types of traps are live- and multiple-capture cage traps. Resourceful farmers are known to invent an amazing array of trapping devices, such as snaring devices or buckets of water with a slippery surface so the rodents fall into the bucket and ultimately drown.

4.1.2 Barriers

Barriers can be built around small areas to protect crops. Plastic barriers have been used successfully for nursery rice crops to protect the seedlings from rodent attack before they are planted out in the field (Sudarmaji et al. 2003). Plastic barriers have also been used around rice fields, but they require regular maintenance. Permanent barriers have been built from bricks and concrete, but there are issues about water flow; drains need to be designed that do not provide access points for rodents. Some species of rodents are excellent climbers, so barriers are not always effective for all rodent species.

4.1.3 Trap-barrier system

One special type of barrier is the *trap-barrier system* (TBS) or community TBS (CTBS). The earliest application of fences plus traps was in Malaysia, where rodent populations had built up in fallow land adjoining rice crops (Lam et al. 1990). This approach was modified to include a trap crop (also called a lure crop) which is planted about 2–3 weeks earlier than the surrounding fields, and thus is slightly more attractive than the surrounding fields (Singleton et al. 1998). Multiple-capture traps are placed inside the fence, along the sides, to capture rodents trying to access the trap crop. Research has found that trap crops of about 50 x 50 m are best, and that this TBS can protect an area of 10–15 ha of surrounding rice fields (Singleton et al. 2003b). This occurs because rats are attracted to the trap crop from about 200 m away (Brown et al. 2003), so at a village scale, several TBSs can be set up to protect a large area of rice (see Section 5.1 for the case study of CTBS in Vietnam).

Interestingly, the TBS was tested in the uplands of Laos and had limited success (Brown et al. 2007). Instead the farmers were more concerned about rodents invading their grain stores. So they modified the approach and placed the fence plus multiple capture traps (facing outwards) around their grain stores. They were very satisfied with the level of management.

4.1.4 Hunting

There are various forms of *hunting* used in different countries. In Laos, rats are hunted using simple bows and arrows or other more sophisticated devices. In Vietnam, farmers work together as a small group, and with the aid of dogs, to locate active rodent burrows, pour water into the burrows and either catch or hit the rats as they emerge from the burrows. In Indonesia, groups of farmers walk in a line through a rice field carrying a string containing tin cans to make noises, and thereby herd rats into a net placed at the other end of the field to catch rats. In Myanmar, rat hunters have made a tool which can produce insect noises to call rats. They kill rats once they come out from their burrows. In the Philippines, rat campaigns may involve a circle of rat hunters that hit rats as they are driven out of a diminishing area of refuge in a fallow field as it is ploughed by a hand tractor.

4.1.5 Habitat management

Another type of physical control is through *habitat management*. Effective management can be achieved through treatment of non-crop areas that are sources of habitat for rodents, often undisturbed weedy areas which provide burrows and nesting sites. This can be managed by slashing the weeds to reduce nesting habitat and increase predation risk. At a broad scale, *crop synchrony* is a highly effective form of management. For rodent species that exhibit a peak in breeding activity that coincides with the ripening stage of rice crops, crop synchrony limits the duration of this breeding period by reducing food availability. However, these measures increase uniformity in rice cropping, which may be in conflict with conservation aims to increase buffer zones and diversify crop margins for the benefit of biodiversity.

4.1.6 Rice bunds

Rice bunds (the small earthen banks surrounding rice field plots) provide an important potential habitat for rodents to construct their burrows. Larger-sized bunds can provide ample space for burrow sites, whereas narrow bunds are not preferred by rodents to build burrows. For *R. argentiventer* and *R. tanezumi*, few rat burrows are found when bunds are less than 30 cm wide and 30 cm high (Brown et al. 2006; Stuart et al. 2015). Thus, minimising the width and depth of bunds to less than 30 x 30 cm is recommended for rodent management.

4.2 Chemical rodent management methods

There are a wide range of *rodenticides* available. These can be broadly categorised as acute and anticoagulant. Acute rodenticides are generally for use in field situations, whereas anticoagulants are not normally registered for use in field settings (normally used in warehouses or houses).

4.2.1 Acute rodenticides

Acute rodenticides cause death from minutes up to 24 hours of ingestion. An acute rodenticide that is widely used by smallholder rice farmers is zinc phosphide (Zn_3P_2). It comes as a grey or black powder, and needs to be mixed with a bait substrate. It is usually mixed and coated onto grains, such as broken rice. It has a garlic odour and is toxic to a wide range of rodent pests (Buckle and Eason 2015). It is available as commercial products in many countries in concentrations of 1–5%, although many countries have banned its use. Phosphine gas is given off in the acidic environment of the stomach, and then the gas enters the blood stream, causing heart failure and damage to internal organs (Buckle and Eason 2015). There is no antidote for the poison. In a relative sense, there are few non-target issues with zinc phosphide because phosphine gas rapidly dissipates and most of the toxic product is released; furthermore zinc phosphide does not bioaccumulate, so it poses not only low secondary hazard but also high primary hazard to many vertebrates and invertebrates (Brown et al. 2002). However, inadequate storage can pose a risk to man and domestic animals.

Rats are suspicious of new objects and some species are known to develop an aversion to the acute rodenticides. When rodents consume a sub-lethal dose and get sick, they learn to associate the illness with the rodenticide, so they will not consume any more. These animals are defined as bait shy. Pre-baiting with untreated grain can be used to reduce bait shyness. However, even with pre-baiting, the use of zinc phosphide is unlikely to achieve a high level of success in rats (Buckle 1999).

4.2.2 Anticoagulant rodenticides

Anticoagulant rodenticides were developed to overcome bait shyness, and they work by blocking the recycling of the active form of vitamin K that is essential for blood clotting. The animal dies of internal bleeding (haemorrhage) several days after ingesting the rodenticide. Thus, it does not associate any sickness with the bait, which allows sufficient feeding to occur. For humans, an advantage of anticoagulant rodenticides is that vitamin K can be administered as an antidote. Warfarin was originally developed for the treatment of human thrombosis in the 1930s, but was found to be an effective rodenticide in the 1940s and became commercially available from 1950s.

The difference between first- and second-generation anticoagulants is that the first-generation anticoagulants require multiple feeds over many days until a sufficient quantity of poison has been ingested. First-generation anticoagulants include pindone, diphacinone, warfarin and coumatetralyl. Rodents generally die within 10 days of ingestion of the bait. Second-generation anticoagulants require only a single feed, but death occurs between 3 and 7 days. Second-generation anticoagulant rodenticides include bromadiolone, brodifacoum and difenacoum. Different baiting strategies are therefore required for the different types of anticoagulants. If using a first-generation anticoagulant, the bait should be available continuously, whereas, if using a second-generation anticoagulant, a pulse baiting strategy should be used. There are significant secondary poisoning hazards for all types of anticoagulants because of the relatively long persistence in tissues of rodents and the way in which anticoagulants can bioaccumulate through the food chain (Eason et al. 2002).

Pulse baiting involves leaving bait in stations for at least three nights and assessing the amount of bait taken. The bait stations should then be removed. After a week, the bait stations should be replenished and left for another three nights, replenishing each night if required. When there is little bait taken, baiting should cease, because most rodents should have been killed. This method reduces the chance of rodents eating excess amounts of bait once they have received a lethal dose, therefore reducing the risk of non-target poisoning. However, this technique requires more effort in checking bait stations; this may incur a greater labour cost, but is much cheaper in terms of the quantity of rodenticide used.

Pre-baiting may be required to obtain effective control of rats because they generally avoid new objects and foodstuffs (neophobia). Pre-baiting allows rats and mice to get used to feeding at a known site and on a particular bait. This ensures that a lethal dose of poison is consumed before illness develops and feeding stops. A sub-lethal dose can lead to 'poison or bait shyness'. The use of the second-generation anticoagulants reduces the need for pre-feeding.

Three types of resistance have been described – operational, toxicological and genetical. Furthermore, the behaviour of rodents, such as neophobia (fear of new objects), and conditioned or unconditioned aversion to the bait base or rodenticide, may facilitate avoidance of ingestion of a fatal dose of a rodenticide. This may explain why application of rodenticides may fail that cannot be accounted for by physiological resistance. Avoidance behaviour, which could be heritable, can and does reduce the efficacy of rodenticides and may also enhance the effects of physiological resistance. There are few documented cases of resistance to anticoagulants in rice-based systems.

Nearly all rodenticides are now out of patent, and there is little work in developing new types of rodenticides (although, see Section 8 on future research). Most research effort is on developing unique attractive bait bases or combining known compounds in bait. Commercial formulations include wax blocks, extruded pellets or bait coated on attractive grain or seed.

4.2.3 Fumigation

Fumigation is used in some countries to gas burrows. In Indonesia, for example, granules of sulphur are mixed with rice straw, placed into a hand-operated fumigation device, set alight, and then air is pumped through the chamber by turning a hand pump and the smoke gets pumped into the rodent burrows (Singleton et al. 1998). Where smoke comes from holes, they are filled with wet mud. The pressure of the pumping pushes the sulphur gas deep into the burrow complex to kill rodents in the burrow. Other types of fumigants include pellets or granules containing aluminium or magnesium phosphide, which are inserted into rodent burrows and sealed with mud.

4.2.4 Repellents

Many repellent compounds have been used for studying the interaction of herbivores and plants using small rodents as model species. Only some studies were aimed at identifying suitable repellents in an applied context. Often repellent compounds work in controlled environments such as laboratories and enclosures but their effects in the field are negligible. As a result only few rodent repellents are registered for controlling rodent damage.

4.3 Biocontrol of rodents

Methods for the biocontrol or rodents include sterility control, reproductive inhibitors, predators and parasites, and diseases.

4.3.1 Sterility control

Currently, there are no effective *sterility control* or *reproductive inhibitors* available for use in field settings. Curcumol and triptolide are registered sterilants for rodent management in China (Huang 2014). It is not clear if they are effective in reducing damage to rice in field situations. A potential chemical sterilant is 4-vinylcyclohexene diepoxide (VCD), which rapidly depletes the follicle population in the ovaries in rats and mice (Jacob et al. 2008). VCD is being considered for registration in the United States.

'BIORAT' is marketed in Vietnam and the Philippines. It is a combination of warfarin sodium 0.02% + *Salmonella enteritidis* var. Danysz Lysine (Painter et al. 2004). There are no published data in mainstream literature to support or refute the use of BIORAT. There are, however, two publications that caution the use of BIORAT because of human health concerns (Friedman et al. 1996; Painter et al. 2004).

4.3.2 Predators

Predators are frequently suggested to reduce the impact of rodents, yet there are very few studies actually demonstrating the impact of increasing predation and increasing rice yields or the yield of other crops. Nest boxes and perches have been suggested as devices for encouraging owls and predatory birds, but no well-designed replicated study demonstrates their effectiveness. The risk of predation can be enhanced through habitat management, which has been demonstrated through giving up densities. Therefore, habitat management is more likely to be effective through increasing predation risk than through increasing perching poles or nest boxes for owls in rice systems.

4.3.3 Parasites and diseases

A number of *parasites and diseases* have been trialled against rodents in rice systems. In general, few have demonstrated increases in rice yields and few are commercially available. A rodent-specific parasite *Sarcocystis singaporensis* has been trialled effectively in rice fields in Thailand and resulted in reduced yield loss and with positive benefit–cost ratios, similar to that obtained with conventional control techniques (Jäkel et al. 2006). Positive results were also obtained when this form of biocontrol was applied as part of an integrated ecologically based rodent management (EBRM) approach in the northern uplands of Laos (Jäkel et al. 2016). The parasitic protozoan needs two hosts to maintain its lifecycle: a snake (*Python reticulatus*) and rodents of the genera *Rattus* or *Bandicota*. Sporocysts of *S. singaporensis* need to be isolated and then mass-produced and inoculated into baits (see Jäkel et al. 2006 for details). The parasite does not infect humans. Currently, this protozoan bait is commercially available only in a few countries.

4.4 Other management strategies

There are some other management strategies that are not strictly physical or chemical, so are grouped here as 'others'.

4.4.1 Diversionary feeding

Diversionary feeding could be used in a situation where high-value produce could be protected by providing an alternative feed source. There are, however, no effective studies demonstrating the benefits of such an approach in rice-based systems.

Table 4 The principles of ecologically based rodent management (EBRM) and attributes of successful EBRM for management of rodent pests in rice crops and how they compare in different country contexts

Principles of EBRM	Southeast Asia (rats in rice fields of Vietnam and Indonesia)	Laos (upland rice systems)	Tanzania
(1) The management actions are environmentally sound	Yes – combination of community trap-barrier system, field sanitation prior to maximum tillering, reduce bund size, synchronise planting and harvesting, destroy rat burrows, conduct community rat campaigns at key times successful for management of rats in rice fields in Vietnam and Indonesia	Partially – combination of targeted trapping in key habitats, targeted community rat campaigns, crop synchrony in lowland pockets of the upland ecosystem, but no widespread effective management strategy has been designed and tested. Rodenticides increasingly available and used	Yes – combination of physical trapping (use of locally made traps), buckets of water buried to the soil surface, field sanitation prior to transplanting, reduce bund size, synchronise planting and harvesting, destroy rat burrows in rice fields
(2) They are cost effective	Yes – beneficial benefit:cost ratios determined	Yes – beneficial benefit:cost ratios determined	No – not sufficiently evaluated
(3) The actions are sustainable	Yes – integrated into government policy	Yes – there is some integration into government policy and at village level	Yes – integrated into village cropping calendar
(4) They are applied at a large scale	Yes – applied at the community scale; management units >100 ha	No – most activities are conducted individually	No – applied at the individual scale; management units <2.5 ha
(5) They are politically advantageous	Yes – integrated into government policy	Partially – some issues highlighted in government policy, but not all	No – integrated into only village cropping calendar
(6) They are socially acceptable	Yes – farmers see the benefit of working together to reduce rat problems	Partially – many farmers are still working individually	No – farmers are still working individually, there is a need for more synthetisation on a change in knowledge, attitudes and practices to farmers for working together to reduce rat problems

Attributes of successful EBRM	Southeast Asia (rats in rice fields of Vietnam and Indonesia)	Laos (upland rice systems)	Tanzania
Understanding of the taxonomy, biology and ecology (behaviour and life history characteristics) of the pest species within the agricultural system	Good understanding of *R. argentiventer* and other species in Vietnam and Indonesia through long-term studies	Reasonable understanding of *R. rattus* complex, but more breeding data and studies on movements and the like are required. More basic information about biology and ecology of rodents involved in bamboo masting outbreaks (*nuu khii*)	Good understanding of *M. natalensis* in eastern Tanzania through long-term studies
Monitoring systems to determine thresholds for management (linked to socio-economic thresholds)	Rodent populations and damage monitored routinely	Monitoring systems not established across the country. Hampered by poor communication and remoteness	Rodent populations and damage monitored routinely by farmers and scientists
Practicing rodent biologists in the region?	Rodent ecologists employed by research and extension agencies	Rodent ecologists employed, but few in number, and few resources	Rodent ecologists and extensionists employed by university and Ministry of Agriculture and food security at rodent control centre agencies, respectively
Experimental field studies used to evaluate management strategies and test hypotheses about rodent population dynamics	Replicated manipulative studies conducted	Observational studies have been conducted, and some treatments have been implemented, but need widespread replicated manipulative studies	Replicated manipulative studies conducted
Consider a range of management strategies – do not rely on rodenticides alone	A range of management strategies are recommended and supported by government initiatives	A range of management strategies are recommended and supported by government initiatives, but more emphasis is needed during widespread *nuu khii* outbreaks	A range of management strategies are recommended by scientists and supported by village local government initiatives

Based on Brown & Khamphoukeo (2010), Brown et al. (2006), Brown et al. (2007), Jacob et al. (2010), Mulungu et al. (2013 & 2015b), Singleton & Brown (1999), Singleton (1997), and Singleton et al. (1999a).

4.4.2 Electricity

Electricity has been used in some countries, but it is a highly dangerous technique for humans. Farmers have been known to tap into the main electricity supply poles through their village and set up a wire 2–3 cm off the ground so that rats are electrocuted. Significant human problems occur, for example, when children play in the vicinity or when adults walk across fields at night. This practice can also lead to livestock deaths and power outages. It is a highly dangerous practice and is not recommended. There are no safe commercially available electrical devices for killing rats in field situations.

4.4.3 Ultrasound and electromagnetism

Some commercial products that emit *ultrasound and/or electromagnetic* pulses are available, but they are designed for use in commercial, warehouse or domestic situations, not for use in large open spaces, such as rice fields. There is little evidence these devices are actually effective.

4.5 Ecologically based rodent management

EBRM is essentially a combination of the control methods mentioned above, but conducted in a manner most amenable to the ecology and biology of the particular rodent pest species and the particular rice agro-ecosystem. EBRM has evolved from an integrated pest management paradigm, but there is more emphasis on specific design of strategies. The initial impetus for EBRM came from Singleton (1997), and has since been further developed. There are six key principles for EBRM, but some additional attributes should also be considered (outlined in Table 4). To develop a successful rodent management strategy, it is important to identify the rodent species of concern and understand its ecology in the specific ecosystem. A few key issues are the timing of control (to take advantage of stage of breeding and population abundance) and undertaking management over sufficiently large areas to reduce the chance of reinvasion after treatment. Case study examples for three countries (Vietnam, Laos and Tanzania) are provided in Section 5.

5 Case studies of management of rats in rice

5.1 EBRM in Vietnam

Rodents are one of the top three rice pests in Vietnam. Farmers describe rodents as the pest they have least control over. Rodents affect households that are dependent on rice production for their livelihoods and impact on poor farming communities which have few resources. Traditionally, farmers have relied heavily on the use of rodenticides, electrocution and spreading sump oil mixed with insecticides onto flooded rice fields to manage the rodent problem, but these can be expensive, are often applied individually by farmers in an uncoordinated manner after significant damage has already occurred, and have negative environmental consequences.

A series of research projects to learn more about the rodent problems were conducted in lowland irrigated rice systems of the Red River Delta and the Mekong River Delta of

Table 5 Ecologically based rodent management strategies that have proven successful to reduce the damage that rats cause to rice crops in Vietnam (based on Huan et al. 2010)

Control action	Reason for action	Timing for management
Community actions	Get the farming community to work together over large areas to identify rodent burrows and destroy them systematically	At land preparation stage up until tillering stage
Synchrony of cropping	Synchronises planting of crops (within 2 weeks) and limits the length of the breeding season of the rats	Needs to be set up prior to land preparation
Rat campaign	Concentrate on source habitats	Before planting
Small bund size in fields	Rats do not dig burrows in bunds smaller than 30 cm wide	Needs to be established before cropping is done
Field sanitation (field hygiene)	Clearing long grass and weeds around irrigation canal banks and other non-crop areas to reduce nesting habitat as well as refuge habitat for rodents when no crop is present	From land preparation to harvest
Community trap-barrier system (CTBS)	To reduce damage to crops through capture of rats	Needs to be established 3 weeks prior to transplanting of surrounding rice fields for best results
Linear trap-barrier system (LTBS)	Plastic fence set up with multiple capture traps to intercept rats moving between source and sink habitats	Can be set up at any time, depending on where rats are residing and where damage is occurring

Vietnam. They were designed to understand the rodent problems in lowland rice cropping systems, the species involved, the nature of damage and the testing of management techniques at a village scale. These projects lead to the development of recommendations for rodent management (see Brown et al. 2006 and Huan et al. 2010 for details). A number of studies were conducted to understand the biology and ecology of the rodent pest species, and it was found that the breeding and behaviour of the main rodent pest species (particularly *R. argentiventer* and *R. sakaratensis*) were linked to the development of the rice crops. Rodent problems increased as the number of rice crops per year increased (up to three rice crops per year), and the level of damage increased through successive rice crops (Brown and My Phung 2011).

Farming communities were trained and supported in implementing EBRM through 'training of trainers' of local extension staff which was built up and expanded over the course of the project. Modules were integrated into national training programmes. Training and supporting activities expanded from core sites each year to neighbouring villages and districts over each subsequent year.

A range of community-based rodent control options were trialled and were found to be relatively inexpensive to implement and resulted in reductions in yield losses. These include community actions such as synchronised cropping, rat control campaigns at key times, field hygiene and the use of CTBS when damage is expected to be high (Table 5).

A coordinated approach was required across communities and villages, and research and extension agencies at the provincial and national levels to implement effective rodent management.

The majority of farmers adopted community actions as a successful rodent control strategy (Brown et al. 2006). The adoption of CTBS occurred only on sites where government subsidies were available to farmers. After implementing EBRM, rodent damage was reduced by 33–50% (reduced by up to 88% in Ha Nam Province), rice yields were increased by 2–5%, rodenticide use was reduced by 62–90% and the use of electrocution was reduced by 95%. There was a strong shift away from individual actions to group or community actions. Key findings to ensure sustainable EBRM include the need to have good coordination between civic and government agencies to enable farmer participation, to have strong, effective leadership of farmer groups and for management to be conducted early in the growth of the rice crop before rodent populations commence breeding.

An additional participatory study was set up with farmers that included the use of a simulation model of rodent abundance and impact on rice yields (My Phung et al. 2013). The model adequately predicted farmer's rice yields and was an integral component of the learning cycle of farmers and extension workers in achieving a clear understanding of the rationale for changing their traditional rodent control strategies. Farmers subsequently timed their rodent control operations earlier than they had practiced before the experiment (targeting the tillering rice crop stage rather than later when rat damage had already occurred) (My Phung et al. 2013). Farmers liked the idea of community cooperation, but it was more difficult to set up and coordinate than undertaking control themselves. They wanted to be able to show they had captured many rats, but they did not want to be embarrassed about returning from rat hunts with very few captured rats.

5.2 EBRM in Laos

In the upland environment, rodents are considered one of the most important pests of upland rice, maize, Job's tear (sorghum) and other crops with mean yield losses estimated at 20% (Douangboupha et al. 2010). Upland rice farmers generally rate them as being second only to weeds as the overall most important constraint to upland rice cultivation (Schiller et al. 1999).

The frequency and duration of rodent outbreaks vary markedly from one province to another. Bamboo masting and rodent (*nuu khii*) outbreaks are episodic, but such population outbreaks occur in many parts of Laos. These are sometimes responsible for extreme crop losses (50–100% losses), occasionally leading to localised or widespread famine. In 2008, severe food shortages due to *nuu khii* outbreaks were reported in seven upland provinces. The main causes of these outbreaks appear to be bamboo masting events and changes in cropping patterns. A number of rodent species are involved in these outbreaks.

The main rodent pest in the upland farming system of Laos is the black rat, *R. rattus* complex. It is found throughout the upland farming system, inhabiting upland crops, lowland systems (in the small pockets of lowland rice along river valleys), and in and around villages. The rodents follow the available food sources between these habitats through the different seasons. It was therefore important to develop rodent management strategies that targeted the rodent populations in the different habitats at key times to reduce damage in the field and damage to produce after harvest.

Farmers in upland environments control rats through traditional methods that include using snap traps, hunting with dogs and sticks, shooting with catapults or arrows, and

Table 6 List of final recommended rodent management strategies for upland rice farming systems in Laos (based on Brown et al. 2007)

Upland	Lowland/garden	Village
• Trap continuously • Use pitfall traps (1 m deep, 0.5 m wide at opening) • Set up bait trap-barrier system (TBS) • Work together to hunt rats in field stores • Work together to hunt rats after harvest	• Trap continuously • Work together to hunt rats after harvest • Set up pitfall traps • Dig burrows and hunt with dogs	• Establish rules/ regulations for sustainable management of rodents (stop use of rodenticide, stop eating predator of rat, promote village campaign and work together) • Raise cats and dogs • Conduct sanitation throughout village • Set up grain store TBS • Get school children working together to trap rats • Conduct village campaign at key times

guarding the field at night with a small fire (Brown and Khamphoukeo 2007). Poisons such as zinc phosphide were also used. Farmers could purchase rodenticides from local retailers, but the product did not have instructions in local Lao language, and the active ingredient was unknown. Rodenticides were applied in the field only when rodent numbers were high, and heavy crop damage had already been observed.

A range of rodent management strategies were designed with farmers, which were then trialled by farmers in 'Treatment' sites through training to implement the recommended activities. Five 'Treatment' and five 'Reference' sites (without management intervention) were established in Luang Prabang and Luang Namtha provinces. Farmers in Treatment sites in Luang Prabang spent significantly more time trapping rats, but overall spent less money applying rodent management practices compared to those in Reference sites. In contrast, farmers in Treatment sites in Luang Namtha spent less time controlling rats but spent more money (one site applied rodenticides that were expensive) compared to those in Reference sites.

Treatment farmers conducted rice store TBS, pitfall traps, sanitation, bait TBS and TBS in the field, and there was an 80% reduction in use of rodenticides in Treatment sites (some villages banned the use of rodenticides) when compared to Reference sites (Table 6).

Rodent damage to upland and lowland rice was relatively low throughout the project, while damage increased from booting to flowering to harvesting stages. There was no significant difference between Treatment and Reference sites, with crop damage for corn 7% (range 0–26%), for lowland rainfed rice 3% (0–16%), for lowland dry season rice 1% (1–2%) and for upland rainfed rice 1% (0–7%).

Moderate levels of breeding in the main pest species (*R. rattus* complex) were evident throughout the year (15–25% adult females pregnant each month). Therefore, management of rodents in villages and neighbouring areas needs to be continuous.

Changes in knowledge, attitudes and practices (Post-KAP) were evaluated at the end of the study (Brown and Khamphoukeo 2010).

- Rodents were a significant pest on farms (88%).
- Effective control methods were trapping (50%), rodenticides (21%), cats (8%) and digging burrows (8%).
- Farmers would continue to use trapping (56%), rodenticides (15%), cats (11%) and digging burrows (7%).
- 78% of farmers wanted to spend less time and money controlling rats.
- 77% of farmers thought that if they used the recommended rodent management strategies they would spend less time and money controlling rats.
- 71% of farmers said they would work together in the future.

5.3 EBRM in Tanzania

In Tanzania, rice production increased dramatically from 985 000 t in 2002 to 2 248 000 t in 2011, owing to expansion of farming areas from 566 000 ha in 2002 to 1 119 000 ha in 2011 (FAOSTAT 2013). Yields, however, have not increased correspondingly (Ching'ang'a 1985) due to several complex factors; one of the most important is food loss due to crop pests, including rodents (Mulungu et al. 2015a). Farmers reported that rodent pests caused 20–60% crop losses in both fields and stores each year (Mulungu et al. 2015b). They often damage crops throughout the growing season, from germination to harvest, causing an estimated 5–11% loss at pre-harvest stages during the wet and dry seasons, respectively (Sixbert 2014). The level of damage, however, was not uniform throughout the growth stages of rice. At planting, for example, rodents dug up and ate the planted rice seeds in nurseries or in fields that were directly planted, and consequently necessitated repeated late replanting and ultimately resulted in lower yields. The rice crop was able to partially compensate for damage, therefore making it difficult to characterise when the damage occurred and its severity. Significant compensation was noted at the transplanting (14 days after sowing (DAS)) and vegetative (45 DAS) stages (Mulungu et al. 2014a).

In irrigated systems in Tanzania, farmers produce rice crops twice per year, one during the rainy season and another during the dry season exclusively under irrigation, and the fields were arranged in a rice–fallow matrix landscape. The recruitment of new rodents into the population was higher in the rice fields compared with fallow land. This could imply that rodents from surrounding areas were attracted to the rice field. Such dispersal into rice fields is most apparent at transplanting and harvesting time where recruitment is highest. Interestingly, recruitment was observed to be low at the booting stage, which is different from what is reported in Southeast Asia. High-quality food resources in rice fields could increase the survival chances of newly born and older rodents during the population increase phase. The multi-mammate rat, *M. natalensis,* had higher survival rates in rice fields than in fallow land, arguably because of enhanced food quality (Leirs et al. 1994; Mulungu et al. 2014b).

M. natalensis is the most abundant rodent pest species in rice crop fields in Tanzania. This genus has been recorded at high densities in disturbed landscape in agricultural fields throughout sub-Saharan Africa (Leirs 1995; Leirs et al. 1996). In irrigated rice fields in Tanzania, its population density fluctuates markedly between months with the highest population peak reported during the dry season (Mulungu et al. 2013). The pest is sexually active throughout the year, although it reaches the highest level when the rice crop is at the maturity stage. Together, this suggests that breeding is highly influenced by the rice production systems, which is different from maize-dominated mosaic habitats. In a maize-dominated habitat, the occurrence of rodent outbreaks is reportedly influenced by rainfall pattern (Linn 1991; Leirs 1995). In irrigated rice agroecosystems, water and food are not limiting factors. Breeding occurs over a longer period and population size is generally higher, with a much weaker link with rainfall (although breeding is still most prominent in the rainy seasons). More juvenile rats are recorded in August and September, indicating that the main breeding season is during the rainfall season (Mulungu et al. 2013). Therefore, the rodents are not influenced by rainfall *per se*, but rather by the quantity and quality of their food, which is dependent on the phenology of the rice crops and surrounding vegetation.

In irrigated rice fields, vegetative plant materials (leaves, stems and seeds) are the most abundant components of the diet of *M. natalensis*, while other food types (invertebrates, fruits) are consumed only in low quantities (Mulungu et al. 2014b). Agricultural cropping patterns in Tanzania typically consist of a relatively small-scale matrix of agricultural fields and fallow land (Odhiambo et al. 2005). Habitat quality for rodent pest species will likely vary according to such changes in land use, and it is expected that the population dynamics of resident animals will exhibit important spatio-temporal differences that can potentially affect crop damage patterns and severity. An understanding of the dispersion patterns of a pest is an important pre-requisite for developing an effective management programme for the pest in question. *M. natalensis* in irrigated rice fields generally exhibited an aggregated spatio-temporal distribution (Mulungu 2015a). Heat maps of trapping grids visually confirmed this dispersal pattern, indicating the clumped nature of captured rodents in irrigated rice crop fields at different crop growth stages (Mulungu et al. 2015a).

Movement of *M. natalensis* in rice fields thus seems to be driven by food availability and flooding status, which can be attributed to land use practices. Adult *M. natalensis* have smaller home ranges than subadults in rice fields, indicating that rice fields are suitable for breeding (Mulungu et al. 2015c). However, travel distances are larger in rice fields, especially at the transplanting stage, during which rice fields are flooded and provide less food. Rats move into neighbouring fallow fields leading to temporary high densities in fallow land. A decrease in travel distance was observed in rice fields when the rice crop is ripening, which can be explained by higher food availability and a more suitable, non-flooded situation.

A majority of farmers (80–90%) cultivate paddy in small fields ranging from 0.5 to 1.5 acres. Therefore, with these small fields, rodent damage to crop is high for small-scale farmers. Current management in rice fields in Tanzania consists mainly of the use of acute rodenticides (53%), trapping and physical measures such as putting polythene around nurseries as rodent barriers (47%) (Mulungu et al. 2015b). Farmers conduct rodent control as individuals. Control actions are reactive, with very little planning and poor safety precautions for the use of rodenticides. The rodenticides in the irrigated rice systems are distributed along the banks of the rice in indiscriminate amounts and with questionable results.

5.4 Principles of EBRM

The six principles of EBRM are compared across the three case studies (Table 4). In order to have effective sustainable rodent management, all six principles of EBRM need to be addressed. EBRM seems to be far more effective in Vietnam than in Laos or Tanzania, mainly related to the longer length of time that research has been conducted in Vietnam. An additional five attributes of successful EBRM are described, and again we see that the attributes are applied better in Vietnam than in Laos and Tanzania. This comparison allows an examination of where the relative strengths and weaknesses exist, and perhaps what could be done to address them. This approach could be applied for any rodent pest in any country.

6 Other vertebrate pests in rice

The other vertebrate pests of rice, such as birds, are not well documented. In Myanmar, munias (*Lonchura* spp.; known locally as rice birds) are considered the main rice field pest according to their foraging habit in rice fields. Other bird pests include sparrows (*Passer* spp.) and parrots (species unknown), especially where crops are ripening earlier or later than surrounding fields. Elephants (*Elephas maximus*) can sometimes become pests in some parts of the Ayeyarwady region and Rakhine State, Myanmar. In Sri Lanka, reported vertebrate pests of rice include elephants, peacocks (*Pavo cristatus*), monkeys (various species) and wild pigs (*Sus scrofa*). In Thailand, munias and weavers (*Ploceus* spp.) are considered to be the main bird pests of rice, with occasional reports of wild pigs and monkeys damaging upland rice (Boonpramuk, U. pers. comm.). In the Philippines, four species of birds are considered pests of rice, including the Eurasian tree sparrow (*Passer montanus*), and three species of munia. The pest status of these birds is not well documented as the only reliable method available to quantify bird damage in rice is the use of bird exclusion nets (Rodenburg et al. 2014). When farmers in Aurora province, northern Luzon, the Philippines, were asked to rank the top three rice pests, birds were ranked as the second most important pest during the previous dry season crop (Stuart et al. 2011).

Bird pests of rice are perhaps best documented in Africa, where the red-billed quelea (*Quelea quelea* L. subsp. *quelea*) can cause severe losses to rice crops over a relatively short period of time due to their gregarious and migratory behaviour (de Mey and Demont, 2013). Based on farmer surveys across 20 countries in Africa, birds are considered to be the second most important pest of rice after weeds (IRRI 2010). Bird damage is most prominent during the dry season, when there are less alternative food sources available, such as wild grass seeds (Ruelle and Bruggers 1982). Preventative measures used to manage bird pests in rice include synchronous cropping; weed control (as weeds attract birds during the early grain filling stage) and nest destruction using avicides, explosives or flamethrowers (de Mey and Demont 2013). Protective measures include the use of repellent substances; protecting fields or nurseries with nets or wires; and bird scaring using humans, noise-making devices, flags or scarecrows. However, aside from weed management that has been shown to reduce bird visitation rates to rice fields (Rodenburg et al. 2014), evidence that clearly demonstrates the effectiveness of these methods is limited.

7 Future trends and conclusion

For several years, no new rodenticidal compounds have been registered for use in crop protection or in the biocidal sector, and this may be the case for years to come.

This is partially due to the availability of effective compounds (anticoagulants) for the management of commensal rodents, which internationally represents a larger market than crop protection. There is some work to identify new compounds such as cellulose-based bait or sodium selenite that seem unpalatable and ineffective (Jokić et al. 2014; Schmolz 2010), methaemoglobin (Rennison et al. 2013) and plant toxins (Pauling et al. 2009; Yuan et al. 2014). Another strategy to improve the efficacy of products is to use a combination bait that includes two anticoagulants, or an anticoagulant and cholecalciferol (Endepols et al. 2016; Baldwin et al. 2016).

Studies on implementing EBRM for rodents in rice cropping systems have provided favourable findings. The studies demonstrate favourable economic returns for the farmers (e.g. Singleton et al. 2005; Brown et al. 2006; Jacob et al. 2010); yet, farmers often do not always continue to practice EBRM. Therefore, more research is required to examine why farmers do not implement such efficient methods, although they know they are effective.

There are opportunities to rigorously explore the synergistic effects of management strategies that have multiple benefits for rice production, for example concurrent weed and rodent management. Entomologists recommend growing flowering plants along the edges of rice fields to promote beneficial predatory arthropods and parasitoids (see chapter 14 in this volume), but this unfortunately provides high-quality food and shelter for rats (Horgan et al. 2016). Bringing together expertise from different fields could be used to explore management practices that have multiple beneficial effects.

Improved monitoring systems and forecasting systems are urgently needed. Most monitoring is conducted too late after damage has already occurred and there are very few predictive models available. Routine monitoring is conducted in some countries (e.g. in Vietnam, Brown and My Phung 2011), but most estimates of rodent impact and damage collected from the field by extension staff are not collected rigorously. There is strong interest in developing automated remote sensing equipment for rodents (in all crops, not just in rice). The challenge is making them reliable and cheap, and not too data intensive. This is a rapidly advancing field. There are also mobile phone applications to record farmer observations, and these will be valuable for region-wide monitoring (e.g. the *MouseAlert* system for mice in Australian cropping systems: www.mousealert.org.au).

Rodents are clearly a significant problem in rice agro-ecosystems in many parts of the globe. The data on post-harvest losses are limited but the published information on pre-harvest losses emphasise the importance of rodent impacts on regional food security (John 2014). One analysis calculated that what rodents eat and spoil globally could feed 280 million people in developing countries for a year (Meerburg et al. 2009b). If rodent damage could be reduced from 10 to 5%, then more rice would be available for human consumption.

It is possible to manage rodent pests and to reduce the damage caused to growing rice crops and therefore increase yields (see case study examples). This outcome occurs primarily through a thorough understanding of the pest species and their breeding dynamics and behaviour, and then a well-supported management strategy that does not rely on a single control technique. It is possible to manage rodents without relying entirely on rodenticides. That is why a good understanding of the rodent ecology and breeding dynamics is required. A range of management methods include crop synchrony, habitat management, management of bund sizes, community campaigns at key times, field sanitation and various trapping methods. Management needs to be linked to a monitoring system and control should be applied early, before significant damage occurs. Finally, management needs to be conducted over a large area. In developing countries that are dominated by smallholder farmers (holdings less than 2 ha), community action is essential for effective management of rodents. We emphasise that food security is a strong driver for EBRM at a village level and also at the national level (see also John 2014).

There are now many examples of well-implemented rodent management strategies, particularly in Southeast Asia. It is possible to learn from these and adapt the processes to other situations. However, more could be done: the rodent problem will not go away; constant effort is required to keep on top of the problem and to continually improve all aspects, including management methods, institutional support and capacity building of extension staff, researchers and farmers.

8 Where to look for further information

Some key resources (web sites, book chapters, etc.) are provided below.

- Singleton (2003) *Impacts of Rodents on Rice Production in Asia* (Published by IRRI): Reviewed pre-harvest rodent impacts for 11 Asian countries.
  - Available at: https://books.google.com.au/books?id=c_nlNaRP2XMC&pg=PA1&lpg=PA1&dq=Impacts+of+Rodents+on+Rice+Production+in+Asia&source=bl&ots=vAH5rCNr8a&sig=YJbXHYMimWmtkSgVU31WmrkHgZk&hl=en&sa=X&ved=0ahUKEwjjjM2fq8_MAhVKv5QKHedGAq8Q6AEIPjAF#v=onepage&q=Impacts%20of%20Rodents%20on%20Rice%20Production%20in%20Asia&f=false.
- Aplin et al. (2003) *Field methods for rodent studies in Asia and the Indo-Pacific* (Published by ACIAR): Described many key methods and approaches needed to undertake studies on rodents. It also contains a description of key rodent pests for the Asia/Pacific region.
  - Available at: http://aciar.gov.au/publication/mn100.
- Singleton et al. (2010a) *Rodent Outbreaks: Ecology and Impacts* (Published by IRRI): Presents chapters from a small conference looking at rodent outbreaks.
  - Available at: http://irri.org/resources/publications/books/rodent-outbreaks-ecology-and-impacts
- *International Conference on Rodent Biology and Management* (ICRBM). There have been five ICRBMs since 1998.
  - All conferences and links to papers are available at http://www.icrbm.org/
- EU-funded projects on rodent management in Africa (StopRats, EcoRat, RatZooMan, StapleRat).
  - More information and links available at http://projects.nri.org/stoprats/background
- *IRRI Knowledge Bank* contains information, fact sheets and links about pre-harvest and post-harvest management of rodents.
  - Pre-harvest available at: http://www.knowledgebank.irri.org/training/fact-sheets/pest-management/rats/rodent-control-non-chemical-in-lowland-irrigated-rice;
  - Post-harvest available at: http://www.knowledgebank.irri.org/step-by-step-production/postharvest/storage/storage-pests/rodents-as-storage-pest.
- Buckle and Smith (2015): *Rodent Pests and Their Control* (2nd Edition) (Published by CAB International): This is the 2nd edition of the classic book. It has been updated and republished.
  - Available at: http://www.cabi.org/bookshop/book/9781845938178.

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