Advances in understanding rodent pests affecting cereal grains

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Advances in understanding rodent pests affecting cereal grains

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1 Introduction

Rodents have been eating our crops, ravaging our grain stores and taking food from our tables for thousands of years. The damage that rodents cause to cereal crops in the field is reasonably well known (pre-harvest losses are 5–15% and up to 100% in some situations; Singleton et al., 2010; John, 2014; Brown et al., 2017), but there is very little understanding about the level of damage that rodents cause to cereals post-harvest; estimates vary widely. This is in contrast to the well-studied post-harvest impacts caused by insect pests (see other chapters in this volume). In this chapter, we review the current knowledge of post-harvest storage impacts by rodents, describe the main pest species, the types of damage they cause, and consider some strategies to manage rodents. We mainly focus on post-harvest impacts by rodents in developing countries, because this is where their impacts are greatest.

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Two earlier reviews of post-harvest losses caused by rodents in cereal systems in sub-tropical and tropical systems (Hopf et al., 1976) and rice in Asia (Singleton, 2003) highlighted that losses are likely to be as high as pre-harvest losses, but there was a dearth of quantitative studies on post-harvest losses. One global estimate was that vertebrates (mainly rodents) caused 5% (approximately 500 million tons) of post-harvest food losses (Cao et al., 2002). Post-harvest losses in some regions may be greater than pre-harvest losses, and reports of 20% losses caused by rodents to grain after harvest are not unusual (Aplin et al., 2003). The FAO estimated that rodent-related post-harvest losses vary profoundly (3–50%) depending on the specific local conditions (Brooks and Fiedler, 1999). Whatever the figure, farmers have gone to the effort of growing their crop, harvesting it, threshing it and then transporting it to grain stores, so the impact can be much greater because the extra time, effort and expense invested have been wasted.

Lund (2015) summarised post-harvest losses for a range of commodities in many tropical and subtropical countries based on earlier work published by Hopf et al. (1976). The main types of storage were stacks, sacks, cribs, warehouses, granaries and temporary structures. The main grain commodities were 'cereals', but rice, maize and barley were listed. The rates of damage or loss ranged from 0.5% to 25% and averaged around 6% (Hopf et al., 1976; Cao et al., 2002; Lund, 2015). Shankar and Abrol (2012) provide a much lower estimate of rodent losses of 2.5% during post-harvest operations (out of a total yield loss of 9.33%); of note is that rodent losses were nearly equal to losses caused by insects (at 2.55%). Given the similar levels of damage with insects, it is surprising that very little attention has been paid to understanding rodent pests in grain storage systems compared to the well-established work on insect pests (in terms of quantifying damage and research and development for improved management). This is further compounded by the difficulty of accurately identifying rodent damage and that farmers are often not aware of the magnitude of chronic losses to their grain stores caused by rodents because they have always lived with such losses.

Rodents cause a range of types of damage to stored grain. Commensal rats and mice are the primary culprits (Table 1). Rodent damage to stored foodstuffs far exceeds the actual value of what they consume. There are direct losses to grain (direct consumption), but there is also spoilage (contamination of grain from hair, urine and faeces) and partial damage which opens opportunities for other pests and diseases to cause further damage (such as insects and moulds). Moreover, rodent gnawing in seed/grain storage structures increases the moisture content of seeds and reduces germination viability of seeds. Spoilage from rodent hair, urine and faeces also increases the risk of disease transfer to humans or livestock (Lovera et al., 2017). Rodents

Table 1 Rodent damage/losses to grains in storage facilities

Country	Species	Damage or loss	Grain and storage structure type	Source
Asia				
Bangladesh	*B. bengalensis*	13%	Lowland	Aplin et al. (2003)
	B. bengalensis	5–10%	Irrigated	http://india.leisa.info/index.php?url=getblob.php&o_id =204244&a_id=211&a_seq=0
India	*R. rattus*	8.62–9.5%	Nadia	Santra and Manna (2008)
	R. rattus *M. musculus*	5.75–6.5%	Burdwan	Santra and Manna (2008)
	Not stated	25–30%	Lowland	Kushwaha (1986)
	R. rattus *M. musculus* *B. bengalensis*	2.5%	Storage: residential premises and farm-level storage	Rao (2003)
	R. rattus *M. musculus* *B. bengalensis*	Not stated	Rural, urban, warehouses and godowns	Shankar and Abrol (2012)
	Not stated	25–30%		Hart (2001)
Indonesia	*R. rattus diardii* *M. musculus* (+ *Suncus murinus*, an insectivore)	Not stated		Sidik et al. (1986)
	Not stated	5–10%	Lowland rice (Sulawesi)	Baco et al. (2010)
Korea	*R. norvegicus* *R. rattus* *M. molissimus*	20% widespread in rural areas		Pest Control Section, Plant Protection Division, Agricultural Production Bureau, Ministry of Agriculture and Forestry, Seoul, Korea (Singleton 2003)
Laos	*Rattus* spp. *Mus* spp.	Up to 10%	Widespread	Direction de'l Agriculture, Vientiane, Laos (Singleton 2003)
	R. rattus	7.4–10%		Brown et al. (2013)
Malaysia	*R. exulans*	Not stated	Common	Crop Protection, Department of Agriculture, Kuala Lumpur, Malaysia (Singleton 2003)
	R. rattus diardii *R. exulans* *R. norvegicus* *M. musculus*	Not stated		Muda (1986)

(*Continued*)

Table 1 (*Continued*)

Country	Species	Damage or loss	Grain and storage structure type	Source
Myanmar	*B. bengalensis* *R. rattus*	7–14%		Belmain at al. (2015), Htwe et al. (2017)
	R. rattus *R. exulans* *M. musculus* *B. bengalensis* *B. indica*	1–14%		Htwe et al. (2017)
Philippines	*R. norvegicus* *M. musculus*	5%		Bureau of Plant Industry, Region VI, Iloilo City, Philippines (Singleton 2003)
Sri Lanka	Still in progress	8%		Htwe (unpublished data)
Thailand	*R. norvegicus* *R. rattus* *R. exulans* *Bandicota* sp. *Mus* spp.	5%	Widespread	Plant Pest Control Research Centre, Plant Industry Division, Department of Agriculture, Bangkhen, Thailand (Singleton 2003)
Africa				
Egypt	Not stated	50%	Maize, wheat, rice, cottonseed in houses and stores	Hopf et al. (1976)
Ethiopia	Not stated	5–15%	Grains in huts on stilts and underground bags	Hopf et al. (1976)
	Rodents and other pests (not insects)	12–20%	Maize, sorghum, teff, barley and wheat in bags in houses	Hengsdijk and de Boer (2017)
Ghana	Not stated	2–3%	Grains, maize, rice	Hopf et al. (1976)
Malawi	Not stated	0.5–1.5%	Maize, groundnuts, sorghum, millet in woven cane bins, grass baskets	Hopf et al. (1976)
	Not stated	15%	Cob maize in cribs	Hopf et al. (1976)
Sierra Leone	Not stated	1–10%	Rice in cane baskets	Hopf et al. (1976)
	Not stated	10–100%	Rice in sacks	Hopf et al. (1976)
	Not stated	2–3%	Rice and maize in roof and cribs	Hopf et al. (1976)
Tanzania	*R. rattus, M. natalensis*	20–60%	Rural household stores	Mdangi et al., (2013, 2016); Mulungu et al. (2015)

Country	Species	Damage or loss	Grain and storage structure type	Source
Zaire	Not stated	3%	Rice and maize in bags in roof	Hopf et al. (1976)
Zambia	Not stated	10%	Cob maize, sorghum, millet in farm cribs	Hopf et al. (1976)
Latin America				
Argentina	Not stated	Not stated	Large silo bags (200-ton capacity) (corn, soybean, forage silage and wheat grains) (survey of stakeholder perceptions: rodents ranked second after armadillos; 14% of respondents claimed that rodents were the main harmful species)	Zufiaurre et al. (2019)
Brazil	Not stated	4–8%	Rice, maize and beans in stacks, sacks and cribs	Hopf et al. (1976)
Mexico	Not stated	5–10%	Rice and maize in cribs, sacks in roofs	Hopf et al. (1976)
Latin America (in general)	*Rattus* spp. *Mus* spp. *Heteromys* spp. *Peromyscus* spp. plus others (see Table 2 for details)	Not stated	Grain stores, farmer's houses	Elias (1984), Rodriguez Muñoz (1993), Brooks and Fiedler (1999)

Source: rearranged and updated after Buckle and Smith (1994), Hopf et al. (1976) and Singleton (2003).

can transfer around 60 diseases to humans including typhoid, paratyphoid, trichinosis, scabies, plague and haemorrhagic fevers like Lassa fever and leptospirosis (Cao et al., 2002; Meerburg et al., 2009). This is particularly dramatic in the context of a developing country; if the main income earner becomes sick, the family can fall into a debt trap (Singleton et al., 2010). This is further compounded because poorly resourced health systems cannot guarantee an appropriate action.

Rodents are one of the few orders of mammals that have continually growing incisor teeth (the other being lagomorphs such as rabbits and hares). To wear down their continuously growing incisor teeth, rodents can gnaw (chew) anything that is not harder than their teeth, which includes copper or iron. These sharp incisor teeth enable rodents to not only eat tough seeds but also cause damage to storage structures made of wood, plastic, plaster and some metals.

The greatest impact of rodent damage occurs in developing countries, particularly in tropical and sub-tropical regions, where facilities are not well developed and where this damage directly affects the livelihoods and food security of rural households and communities (Singleton et al., 2010). In many of these countries, the infrastructure for grain storage is rudimentary and can be as simple as a woven basket in a thatched house or a simple wooden or corrugated iron grain store, which is no match for rodents. The main staple cereal grain stores are all affected by rodents and include all the major grain types, including maize, rice, wheat, barley, sorghum, millet, oats, rye and triticale (other raw or processed food commodities are also affected, including grain pulses, root crops, fruit, vegetables and nuts). Grain is stored either in houses or in adjacent small grain storage structures made with locally available materials. The extent of stored grain and seed losses during storage depends on the farmers' practices of harvesting; storage structure; sanitation around the storage area; the duration of storage; and the distribution, abundance and species composition of rodents in the area (Belmain et al., 2006; Htwe et al., 2017). Losses by rodents in developed countries can also be high, but, again, there are very few quantitative studies. In Australia, occasional outbreaks of house mouse populations can lead to problems of contamination of wheat with carcasses and droppings. In some years the wheat that is uploaded to ships for export has to pass through fine screens, which increases considerably the time taken to complete a shipment. The cost associated with this is considerable. New developments in storage technologies are becoming more common and include large silo bags (60-m long plastic tubular bag laid on the ground with 200-ton capacity) and have been adopted in more than 50 countries (Abadía et al., 2013). These pose new risks by rodents and other vertebrates (Zufiaurre et al., 2019).

There are only a small number of studies where rodent damage has been directly measured, and these have been mainly undertaken in the last 10 years or so. These studies compare losses from a known quantity of grain samples from paired containers allowing (open) or denying (closed) access by rodents. Thus, in a comparative way, losses over time can be determined. These are expanded in the following section. Nonetheless, a huge gap remains in our understanding of post-harvest impacts caused by rodents.

2 Impact of rodents on stored grain

There have been different approaches to look at the impact of rodents on grain stores. Surveys of farmers have explored post-harvest impacts of rodents, and more recently there have been comparative studies on quantitative losses from grain stores. Some measurements are incidental observations made during assessments for insect pests. As Singleton (2003) stated in a review of impacts of rodents on rice production in Asia, post-harvest losses are probably of a similar magnitude to pre-harvest losses. However, the data were patchy and there have been few studies of the impacts of rodents on post-harvest storage of rice at the time of writing. According to Singleton (2003), it was clear that rodents played a significant role in influencing food security and poverty alleviation programmes for the rural poor in Asia. Furthermore, in many Asian countries, farmers simply accept post-harvest losses, partly due to the lack of simple and effective methods of control (Singleton, 2003). A similar scenario occurs with poultry farmers in Argentina (Cavia et al., 2019). There are also unquantified impacts on household nutrition and health through potential transmission of gastroenteric diseases and zoonoses to humans and livestock (Belmain et al., 2015). It is likely this situation is similar in other regions. Unfortunately, there are few comprehensive studies, and so there are many gaps in our knowledge.

Singleton and Petch (1994) conducted a review of rodent pest impacts through Southeast (SE) Asia with a primary focus on pre-harvest impacts, but they considered post-harvest impacts too. They reported on responses by government staff from many SE Asian countries. Many responses confirmed that rodents were a problem in grain stores, but they were not sure which species were involved. In Laos, there was a major problem in the uplands (hilly regions of Laos). For Malaysia, there was no information available. For the Philippines, *Rattus* spp. were responsible for post-harvest damage. There were no estimates of losses provided.

Ahmad et al. (1995) studied rat populations (*R. rattus*) in wholesale grain markets in Pakistan. The estimated population size ranged from 5 to 61 rats per grain shop. They determined in the laboratory that rats ate 12.7 g of rice each night and estimated the annual grain loss per shop was 740 kg (consumption, contamination, spillage and wastage). After scaling up to all markets across the country, annual losses would be approximately 4000 mt/year or 0.3% of the estimated 1.225 million mt that passed through the markets each year.

Parshad (1999) reviewed the rodent impacts to agriculture in India and summarised rodent losses post-harvest. There were 18 rodent species identified, but only 4 species seriously affected grain stores (in houses and godowns/warehouse; *B. bengalensis*, *Rattus norvegicus*, *R. rattus* complex, *M. musculus*). Parshad (1999) summarised many quantitative assessments of rodent infestations in a range of houses and market premises with around 8 house rats per premise and 11 rats per godown, with much higher estimates in some cases (thousands of rodents). Levels of damage were less in situations where grain was stored in metallic bins (0.1%), compared to samples of spilled grain collected from flour mills, grain stores and houses (4.7%). High levels of damage were attributed to inadequate maintenance of buildings, combined with a lack of hygiene and poor handling of food materials, leading to spillage and neglect of rodent proofing. Many grain stores were made from traditional materials such as clay, wood, bamboo, straw, jute bags and bricks, which were considered vulnerable to rodent attack.

Cao et al. (2002) calculated that, globally, vertebrate pests accounted for 5% of post-harvest food losses, mostly attributed to rodents. They stated that the levels of loss were lower in developed countries because of well-designed food storage and processing systems. There are very few studies from developed countries. However, one study, by Wildey (2002), reported the results from a farm survey in the United Kingdom that rodents infested about 70% of grain stores.

Von Maltitz et al. (2003) surveyed farmers in Limpopo province of South Africa to ask about post-harvest impacts, including rodents. Rodents were often ranked as the most important post-harvest constraint for a range of stored crops in Limpopo. Rodents were ranked number 2 after insects affecting stored sorghum and maize.

In a chapter in the book *Integrated pest management in stored grains*, Shankar and Abrol (2012) largely focussed on insect pests, but they summarised some relevant material for the post-harvest impacts of rodents in India. They reported that rodents caused losses of 2.5% (out of a total of 9.3%). The main species attributed to damaging stored grains in India were *R. rattus*, *M. musculus*, *B. bengalensis* and *B. indica*. In contrast, Hart (2001) reported that overall losses of grain to rodents in India were approximately 25% in pre-harvest and 25–30% in post-harvest situations, bringing the loss to at least US$5 billion annually in stored food and seed grains in India.

Brown et al. (2013) set out known amounts of rice grain in open and closed metal bowls in farmers' grain stores in Lao villages and monitored weight loss over time. Weight loss attributed to rodents was 10.3% in the dry season and 7.4% in the wet season, enough grain loss that could have fed a Lao household for 1.5 months. There was a weak but positive relationship between rodent droppings and rodent losses. Unfortunately, Brown et al. (2013) were unable to determine if rodent damage was associated with any particular environmental condition in or around the grain stores.

Mdangi et al. (2013) studied rodent damage to stored maize in smallholder farms in Tanzania. There were significant differences in damage, loss and contamination between different storage structures. They ranged from 0% in closed sacks to 7.9% in closed cribs, 17.7% in open sacks and up to 40.4% in open cribs. There was a strong positive relationship between the number of rodent droppings per month and damage to stored maize. *R. rattus* was the main rodent species.

Belmain et al. (2015) set out known amounts of rice grain in open and closed baskets in farmers' grain stores in rural Bangladesh and Myanmar. Comparisons were made between areas where rodent control was carried out and areas where it was not. Where no rodent control was conducted, losses were 2.5% in Bangladesh and 17% in Myanmar. Where rodent control was conducted, losses were 0.5% in Bangladesh and 5% in Myanmar. Rural households in Bangladesh were losing more than 70 kg of rice per year, which was enough to feed a family for 3–4 months. Daily rat trapping reduced losses.

In Myanmar, Htwe et al. (2017) estimated post-harvest losses by rodents of 4–14%. The loss of 481 kg of rice by rodents from grain stores was considered enough to feed a family for 4 months. The gnawing habit of rodents caused an additional loss; the average loss of rice seed stored in different bags was 4.5 ± 2.1%, and germination loss was 43.1% by rodents gnawing different storage bags in Myanmar (Maw, 2017). In Myanmar, rodents' faeces were counted from grain collected near the surface of the stored grain (stored as loose grain in the grain store) and the estimated contamination rate was 0.01–0.02% (Htwe et al., 2017). See the case study for Myanmar below.

Swanepoel et al. (2017) carried out a systematic review of rodent pest impacts to quantify and identify trends in the impact of rodent pest research on small-holder agriculture in the Afro-Malagasy region. This work identified 19 out of 162 publications with data on post-harvest losses, from which the authors calculated median storage losses of 7.9% by rodents from across the studies.

Edoh Ognakossan et al. (2018) examined rodent impacts on stored maize in Kenya and found the cumulative weight loss ranged from 2.2% to 6.9% in shelled cobs and from 5.2% to 18.3% in dehusked cobs after storage for 3 months. *R. rattus* was the only species trapped. The study confirmed that there were significant increases in mould, *Fusarium* spp., and aflatoxin contamination in rodent-damaged grain.

For Latin America, it is not clear what species cause losses or the extent of the damage because there are very few studies of the post-harvest impacts by rodents to grain storages (Table 1). One study published by the FAO (Kravets, 1991) stated that most grain stores (silos) were well constructed and grains pass through quickly. The presence of rodents was observed in general around the silos but mainly fed on spilled grains in loading areas. The rodent species were not identified, and no estimates of damage or loss were provided. A survey of stakeholder perceptions in Argentina identified that rodents were the second-largest concern for farmers in terms of damage to large silo bags (after armadillos; Zufiaurre et al. 2019). Nearly 60% of respondents reported that rodents caused damage to large silo bags and that 14% of respondents claimed that rodents were the main harmful species (Zufiaurre et al., 2019). The rodent species were not identified. There are also several other studies in Argentina reporting impacts on pig, dairy and poultry farms (*R. norvegicus*, *R. rattus* and *M. musculus*; Miño et al., 2007; Fraschina et al., 2014; Lovera et al., 2019). Therefore, by association, it is presumed these are also the main rodent pests in post-harvest grain stores since their distribution within farms is associated to livestock food sources (Lovera et al., 2015; Montes de Oca et al., 2017; Lovera et al., 2019). The likely post-harvest pest species for Latin America are further considered in Section 3.

3 Rodent pest species and their biology

The key rodent pests of grain stores are the '*R. rattus*' complex (see below), *R. exulans*, *M. musculus*, *B. bengalensis* and *B. indica* (Tables 1 and 2), but this depends on the country (Table 1). The '*R. rattus*' complex is responsible for major post-harvest losses in many countries (Aplin et al., 2003). The '*R. rattus*' complex and *M. musculus* have a world-wide distribution, and it is interesting to note that the brown rat (*R. norvegicus*) is not really considered an important post-harvest grain storage pest, although it is implicated in some publications (e.g. in India, Parshad, 1999). '*Rattus rattus*' complex, *R. exulans* and *M. musculus* are excellent climbers and are well suited to invading grain stores. The multimammate rat (*Mastomys natalensis*) is implicated in post-harvest losses in some parts of sub-Saharan Africa, but captures are less than the '*R. rattus*' complex (Mdangi et al., 2013).

The biological and ecological features for three of the main rodent pest species are shown in Table 3.

There is much scientific debate about the origins and number of species belonging to the highly invasive '*R. rattus*' complex (which goes by numerous common names: black rat, ship rat and house rat but are all part of the '*R. rattus*' complex). The story about this species is a story about human history, evolution and expansion itself. While it is generally considered that the Indian peninsula is the original home of *R. rattus*, there have been multiple origins of commensalism, and thus there is variation in the rat's genome, hence the nomen '*R. rattus*' complex (Aplin et al., 2003, 2011; Baig et al., 2019). There are four major lineages, each showing a different expansion and evolution, which mirror patterns of human dispersal and trade over the last hundreds to thousands of years (Aplin et al., 2011). There are similar stories about the other main commensals *M. musculus*, *R. norvegicus* and *R. exulans*.

Identifying the main rodent pest species affecting post-harvest grain in Latin America is difficult. There are several FAO publications summarising the likely species (e.g. Elias, 1984; Rodriguez Muñoz, 1993), but there is confusion about some of the taxonomy and few studies have measured damage or

Table 2 Key rodent pest species that cause damage to stored grains

Region	Rodent species	Common name	Remarks
Worldwide	*Rattus 'rattus'* complex	Black rat, ship rat, house rat	Widespread and common
	R. norvegicus	Brown rat, sewer rat	Widespread and common
	Mus musculus	House mouse	Widespread and common
Asia	*Bandicota bengalensis*	Lesser bandicoot rat	Commensal
	Rattus exulans	Little house rat, pacific rat	Commensal
Africa	*Mastomys natalensis*	Multimammate rat	Commensal
	Acomys cahirinus	Spiny mouse	Commensal
	Arvicanthis niloticus	African grass rat	Peri-domestic
	Gerbilliscus spp.	Gerbils	Peri-domestic
Latin America (updated from Brooks and Fiedler 1999)	*Calomys laucha*	Vesper mouse	Wild, sylvan and peri-domestic
	C. musculinus	Vesper mouse	Wild, sylvan and peri-domestic
	C. callosus	Vesper mouse	Wild, sylvan and peri-domestic
	Akodon azarae	Grass mouse	Wild, sylvan and peri-domestic
	Sigmodon hispidus	Cotton rat	Peri-domestic
	Oligoryzomys longicaudatus	Rice rat	Peri-domestic
Latin America (updated from Elias 1984; Rodriguez Muñoz 1993)	*Heteromys anomalus*	Trinidad spiny pocket mouse	Wild and sylvan
	Peromyscus spp.	Deer mice	Peri-domestic
	Ototylomys spp.	Big-eared climbing rat	Wild and sylvan
	Eligmodontia spp.	Gerbil mice, laucha	Grasslands
	Neotoma spp.	Packrat, woodrat	Wild, but some found in houses
	Proechimys spp.	Spiny rat	Wild and sylvan

Source: adapted and updated from Elias (1984), Rodriguez Muñoz (1993), and Brooks and Fiedler (1999). Note the different species for Latin America as listed by Brooks and Fiedler (1999), Elias (1984) and Rodriguez Muñoz (1993) (see text for details).

losses. Elias (1984) summarised rodent species in Latin America. Of the 124 genera (593 species), 41 were implicated as pests and 8 were implicated as pests in stored products. The four genera recognised in Latin America as pests of stored products are *Heteromys*, *Peromyscus*, *Rattus* and *Mus* (Table 2). Other genera were suspected including *Ototylomys*, *Eligmodontia*, *Neotoma* and *Proechimys* because they have appeared in places such as houses and warehouses (Elias, 1984; Table 2). Rodriguez Muñoz (1993) also listed these

Table 3 Summary characteristics of the three main widespread and common rodent pest species

Characteristic	*Mus musculus*	*Rattus rattus* complex	*Rattus norvegicus*
Common name	House mouse	Black rat, roof rat	Brown rat, sewer rat
Adult size HB = head + body, T = tail, W = weight	HB = 60–95 mm T = 75–95 mm W = 10–20 g	HB = 160–205 mm T = 185–245 mm W = 95–340 g	HB = 180–255 mm T = 150–215 mm W = 200–400 g
Description	Small size. Tail length about same as H + B. Wide range of body colours	Body slightly smaller than *R. norvegicus*, large ears. Tail length > H + B	Body slightly larger than *R. rattus*, large head with small ears. Tail length < H + B
Litter size	1–10 (average 5–6)	1–10 (average 6-7)	1–12 (average 6–7)
Diet	Omnivorous	Omnivorous	Omnivorous
Nesting habitat	Subterranean, buildings	Buildings (especially roofs)	Subterranean
Gestation period (days)	19–21	20–21	20–21
Age at sexual maturity (weeks)	5–8	8–10	8–10
Feeding habitat	Fields and buildings	Trees, fields and buildings	Buildings
Neophobic (fear of new objects)	No. Mice will readily explore new items found in their territory and try new food.	Yes. Rat will not explore new items or new foods readily.	Yes. Same as for *R. rattus*.
Communication of food preferences to other animals	Rarely	Not known	Yes
Effectiveness of 1st generation anticoagulants	Low	Low	High
Colour vision	Colour blind	Colour blind	Colour blind
Sense of smell	Acute	Acute	Acute

species. In contrast, Brooks and Fiedler (1999) listed a different set of rodent species that are likely to cause post-harvest losses (*Calomys laucha*, *C. musculinus*, *C. callosus*, *Akodon azarae*, *Sigmodon hispidus* and *Oligoryzomys longicaudatus*) (Table 2). Elias and Fall (1988) mentioned *Akodon* and *Calomys*, and Gómez Villafañe et al. (2005) mentioned *C. laucha* as probable pests on stored grain. It is clear, therefore, that further research work is needed to understand the species and levels of damage or losses caused by rodents to grain stores in Latin America.

The commensal species (species that are highly adapted to modified human environments and live along-side humans) are well adapted to highly modified environments of grain stores. In many countries, the pest rodents identified in the field are different to those species identified in grain stores. For example, in Indonesia, the main field pest is the ricefield rat, *Rattus argentiventer*, but it is likely that the main grain storage pests belong to the '*R. rattus*' complex. In Tanzania, the main field pest is *M. natalensis*, but, again, a species belonging to the '*R. rattus*' complex is the main pest in grain stores (Mdangi et al., 2013).

Whilst the species or rodent might be known, information about its biology (breeding, habitat use, movements, etc.) is not well understood in post-harvest situations. There are a few studies examining the habitat use and movements of rodents in and around grain stores. One of these is by Aplin et al. (2003), who studied movements of a species of the '*R. rattus*' complex in and around rice fields and village environments in upland regions of Laos, where grain stores are built within village environments. The '*R. rattus*' complex species is the dominant pest in both village and field habitats. Many individual rats sheltered in piles of freshly harvested rice straw and Job's tears stalks (*Coix lacryma-jobi* or adley millet) immediately post-harvest. Numbers of rats increased in villages shortly after the harvest was complete. In essence, these rats were following food resources from rice fields into the village areas where the grain was being stored (Aplin et al., 2006). The implication is that the management of grain stores needs to be considered in the light of surrounding habitats (crops, houses, intensive livestock, etc.).

Ahaduzzaman and Sarker (2010) reported from farmer surveys that rodent numbers during a bamboo flowering (and masting) event peaked in Chittagong Hill Tract (Bangladesh) around the time of rice harvesting, with high numbers continuing into the post-harvest period.

In Myanmar, some rodent species, particularly *B. bengalensis*, are well known for their hoarding behaviour. The amount of stored grain in the burrows under rice piles was 8.7 ± 5.7 kg measured at 4 weeks after piling. This was equivalent to 3% of the total rice yield (Htwe et al., 2017).

A good knowledge of the changes in abundance, movement patterns, breeding dynamics and nesting site locations would enable improved management strategies to be developed. This would allow managers to better target the location and timing of control strategies. Until more is known, managers will continue to apply control practices indiscriminately. Rodent management strategies are outlined in Section 5.

4 Types of rodent damage

Upon close inspection, rodent damage to grains stores should be obvious. There should be ample evidence of rodent faeces/droppings and, in heavy infestations, smear marks along walls and runways. There might also be evidence of gnawing along walls, floors or ceilings, especially on wood. Damaged grain can be discerned by relatively obvious teeth marks from rodent gnawing.

Under normal conditions, rodents are wasteful eaters, biting out small pieces of grain and often discarding the remainder. Thus, the potential loss to crops and to stored produce by rodents is much higher than they have actually consumed (Cavia et al., 2019). Some rodent species, especially from the genus *Rattus*, tend to only sample small amounts of food from numerous food types. In general they are neophobic, meaning they tend to avoid new objects or food stuff. In reality, this may not necessarily be true in grain stores, where there is often a super-abundance of one or more food types, so these species are likely to readily consume these grains.

Rodents typically hold a cereal grain in their front paws, holding it at each end and then rapidly de-husking the grain with their teeth. They then turn it and eat it like a banana. As they nibble, they rotate the grain. Not all of the grain is eaten; some parts are discarded and appear to be coarsely ground (kibbled). Rodents that are hungry tend to eat more of the grain than those that are not hungry; they tend to take more time handling the grain but still discard grains after only a few bites.

Rodents tend to concentrate on the germ of seeds where there is a rich source of unsaturated fatty acids and proteins with the best amino acids (Edoh Ognakossan et al., 2018). By removing the germ rodents reduce the nutritional value of the grain and its potential for germination (Edoh Ognakossan et al., 2018).

Contamination and spoilage from hair, urine and faeces is a real concern. A single rat can leave behind around 25 000 droppings each year and produce over 3 litres of urine each year. There is also structural damage not only to grain stores or facilities (including physical damage to wood or metal structures) but also to bags (spilling contents) and to electrical wiring, water pipes and other infrastructure. The costs of rodent damage are thus far greater than the economic loss from the damaged grain itself.

Apart from the obvious direct consumption of grain and from spoilage, impacts of rodents on stored grain for smallholder farmers in developing countries can lead to less food availability in the market, increased price of food, people worrying whether they will have enough food to eat as time progresses post-harvest, lower quality seed in the market for subsequent crops and changes affecting lives or short-term risks to lives (Ahaduzzaman and Sarker, 2010).

5 Strategies to reduce rodent damage

5.1 Principles for rodent management in grain stores

There are some basic principles about reducing damage by rodents to grain storages that should be followed. The best approach is to use an integrated pest control strategy using preventative and control measures that consider environmental, ecological and socio-economic factors to effectively control pests. These can be modified according to the situation and can be applied in a broad sense in developing and developed countries alike.

1 *Deny access* – prevent rodents from accessing the food grains in the first place. In reality, it is difficult to make grain stores rodent proof, particularly if they are old or in poor condition. Choose dry, tight storage facilities (Cao et al., 2002). The tight storage units require solid doors, ventilation and construction. In the smallholder context in Africa, Mdangi et al. (2013) suggest using closed storage (bags or cribs) and improved storage structures to reduce rodent damage. Sacks were more expensive and required wire mesh protection, but they led to fewer losses and a higher cost–benefit ratio.
2 *Prevent borrowing and nesting sites* – ensure there are no opportunities for rodents to live within the confines of storage structures. Raise grain stores off the ground, open up cavity walls and so on.
3 *Use a combination of control strategies* – which include rodenticides and physical methods. A range of rodenticides and physical control strategies are outlined in the following sections. Avoid using cats and dogs. There are no experimental studies demonstrating the success of these predators in grain stores. Also, cats and dogs are at risk of secondary poisoning from rodenticides if they are used as a control strategy, and both are carriers of diseases that affect humans. Continuous trapping using inexpensive kill-traps was shown to reduce rodent damage to grain stores in villages in Myanmar and Bangladesh (Belmain et al., 2015). However, this approach is less acceptable in Myanmar because killing animals is not readily accepted by Buddhists; Buddhism is the most commonly practised religion in Myanmar.
4 *Prevent access to food resources* – general hygiene around grain stores (removal of rodent harbour such as plants and piles of rubbish) and good cleanliness are the key here. If there are no spillages, then there is no free food for the rodents.
5 *Monitor effectiveness of programmes* – how do you know you are being successful? Conduct routine inspections and use a simple method for detecting rodent activity or abundance (trapping, foot tracks in powder, etc.) before and after management is implemented.

5.2 Rodenticides

A wide range of rodenticides are available. All must be placed in bait stations or boxes to prevent accidental spillage or access by children, domestic pets or livestock. They can be categorised into four main groups as follows:

1 *Sub-acute* (single or multiple doses, slower-acting).
2 *Acute* (single-dose, fast-acting; hours to 1–2 days).
3 *First-generation anticoagulants* (multiple dose, slow-acting, can take up to 10 days for the animal to die).
4 *Second-generation anticoagulants* (single-dose, highly potent, slow-acting: death of rodents occurs at around 4–7 days).

Although rodenticides are often used as the primary method for controlling rodents in grain stores, a combination of control strategies are required. One of the significant drawbacks of using rodenticides is that the rodenticide baits need to be sufficiently attractive in order for a rodent to take and eat them. This is very difficult if high-quality alternative food is present, in the form of the stored grain.

Von Maltitz et al. (2003) reported from farmer surveys focused on rodent problems that 40% of respondents used a preventative method against rodent damage. The most common method was the occasional single-dose use of a chronic rodenticide in and around the house and food store. Rodent species identified were *R. rattus*, *R. norvegicus* and *Mastomys* spp., with *R. rattus* being the dominant species trapped at the time of the survey.

Meerburg et al. (2004) indicated the following four factors that determine the uptake of a rodenticide bait:

1 Whether the rodents are neophobic or neophilic.
2 The population structure of the target rodent population.
3 Bait palatability.
4 Habitat structure, including access to alternative food.

There are a range of repellents and fumigants also registered for rodent management but are not discussed here in detail because they are not very effective in managing rodent populations.

Sub-acute rodenticides are beneficial if a lethal dose has been ingested by the target rodents before the onset of anorexia, but there is a disadvantage if a sub-lethal dose is taken (Buckle and Eason, 2015).

The anticoagulants were originally designed to circumvent the neophobic feeding behaviour of rodents (particularly the species of the '*R. rattus*' complex and *R. norvegicus*), where they sample only small amounts of new food types. The first-generation anticoagulants required multiple feeds, but the second-generation anticoagulants are more potent and need only a single feed. As the name suggests, the anticoagulants inhibit the clotting of blood, and death normally occurs through organ failure and internal bleeding and can occur at 4–10 days, depending on the active ingredient and dose. In general, anticoagulant rodenticides have a high efficacy, are easy to use, are inexpensive and, if applied correctly, have a minimal environmental risk when adequate mitigation measures are properly applied (Jacob and Buckle, 2018). There is a risk of secondary poisoning with the anticoagulants – they can accumulate through the food chain. Animals that accidentally ingest anticoagulants can be treated with vitamin K, which is readily available.

The anticoagulants are now an integral component of rodent management around the world and in a wide range of situations from food processing (in bait stations), grain storage, intensive livestock systems, households, to commercial properties, but genetic resistance has developed in many countries (Rost et al., 2009). Testing for genetic resistance in rodents is routine in Europe (Pelz et al., 2005; Prescott, 2003) but not in many other countries globally. Furthermore, the effects of rodenticide on wildlife via primary and secondary poisoning have not been adequately tested (Lohr and Davis, 2018).

Cellulose baits (powdered corn cob) have been suggested as an alternative to traditional rodenticides (Schmolz, 2010), but there is no credible evidence that cellulose baits work. Schmolz (2010) reported that all test animals died in no-choice tests, and in choice trials 11 of 12 rats survived. If alternative food is available (such as in grain stores), these baits do not work.

Rodenticide baits need to be placed in bait stations, but these need to be where rodents are likely to encounter them. In developed countries because of the requirement for compliance with regulations, bait stations in warehouses and commercial premises are serviced under contract by pest control companies and visited every 4, 6 or 8 weeks to replenish baits. Bait stations are necessary to reduce spillage and minimise non-target poisoning. Endepols et al. (2003) described a scheme to compare the effectiveness of allocating rodenticide baiting points to specific structural elements or only where obvious signs of rat activity occurred. They looked at 25 farms and monitored activity before and after treatment. Rat control was often conducted irregularly and with poor preparation and documentation (especially on small- and medium-sized farms). Complete rat eradication was achieved on many farms. A ≥75% level of implementation of the control plan always resulted in complete control success.

5.3 Physical and other management practices

A key component of any pest management is to manage the environment to reduce pest incidence, essentially to deny them access to nesting sites and to expose them to increased predation pressure. This can be achieved through habitat management and physical management. It is often impractical in grain stores to have rodent-proof buildings and eliminate food sources, but reducing habitat complexity might disadvantage rat populations, through increased exposure to predation or reduced opportunities for nesting. Rats actively avoid predators and prefer to stay close to cover when moving between nesting and feeding sites (Lambert et al., 2008; Jones et al., 2017). In grain stores food is freely available for rats throughout the year. It is likely that the home range of rodents in grain stores will be small (Gómez Villafañe et al., 2008), so they do not need to move far to find food. Habitat management is important, but Brown et al. (2013) could not determine the key attributes that led to rodent losses in grain stores in Laos.

Targeted habitat management has the potential to reduce the size of rat populations and should be used as part of an integrated management approach for rats (Lambert et al., 2008). It is recommended that at least 20–30 m (corresponding to the average home range size) should be maintained free from vegetation and other harbourage around storage structures where food resources are located (Montes de Oca et al., 2017). Wire netting can also be installed to exclude rodents (hole size < 6 mm) from electrical boxes and access through holes and gaps in walls and so on (see Mdangi et al., 2013).

There are different types of traps commercially available. These can be grouped into single-catch snap traps or cage traps and multiple capture live-traps. Each of these requires time and effort to set up and check. They also need to be baited with an attractive food type (e.g. peanut butter and bacon are good lures), and they need to be positioned so that rodents encounter them (i.e. along edges of walls or on roof beams). Unfortunately, because of the neophobic behaviour of rats, it is necessary to move traps around and perhaps leave them baited but unset for several days to reduce the neophobic response of rodents to new objects in their environment. Glue boards are not recommended.

Cats are important predators of rodents and have exerted strong selective pressure on the behaviour and physiology of rats. Cats are sometimes suggested to help control rodents. Mice and rats caught by these cats may be intermediate hosts for parasites such as *Toxoplasma gondii* (Meerburg et al., 2004). Excrement from infected cats can then pose a hazard to the health of farm animals and humans. Apart from the health risk presented by cats, there is no sound evidence that cats regulate rodent populations. In one study, Mahlaba et al. (2017) found that rodent activity decreased in farm homesteads in Africa where cats were present, but there was no decline in rodent abundance.

6 Case studies

6.1 Case study 1: community village-level rodent management in Myanmar

The study was conducted in Maubin Township (Ayeyarwaddy region) and Daik U Township (Bago region) in 2015. A community village-level rodent management system including trapping, sanitation around storage houses and installing rodent-proofing (installing nylon open mesh at the access route of rodents) was conducted in three villages. Sanitation included regular sweeping, the removal of materials under and around the storage structure (breeding sites for rodents) and cutting tree branches that can provide access routes for rodents to grain stores. Plastic kill-traps inside the stores and bamboo snare traps outside the stores were set for two consecutive nights every 2 weeks. Evidence of rodent contamination and weight loss in two standard 8 kg baskets (rodents had access to one basket but not the other) was quantified. This management strategy commenced at the beginning of the time of storage of rice until 2 weeks after the stores were depleted of grain. This system reduced rodent losses from 4% (28 kg) to 1% (7 kg) (Fig. 1) (Htwe et al., 2017). The cost for managing rodents was 16 250 kyats (US$14/house); farmers could benefit by 94 770 kyats (US$81/house).

In 2016, a farmer-led village-level rodent management system was conducted in Maubin Township (n = 40 families). A focus group discussion was conducted at the end of the storage season to document the farmers' adaptive practices. All farmers' stores installed rodent-proof nylon (open mesh); 50% of farmers followed the sanitation recommendations, but only 10% of farmers implemented trapping. The recommended management practices were simple to follow. However, only 10% of farmers followed the entire package of recommended practices and 90% identified a range of challenges; which included the following:

1 Farmers have their individual storage house, and they do not tend to work together as a community for rodent management.

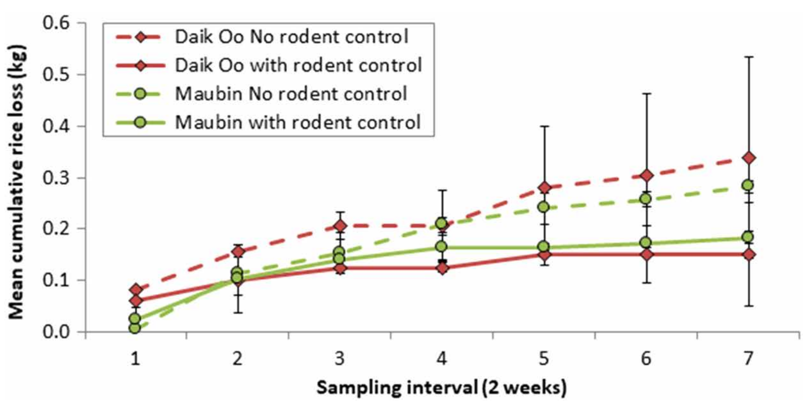

Figure 1 Cumulative increase in rodent damage to rice in grain stores in Myanmar (dashed lines) in comparison to sites where rodent control was undertaken (solid lines).

2 Their store house was also used as a storage area for farm machinery, and cleanliness in and around stores remained poor.
3 Most farmers were reluctant to use the snap traps as it was culturally unacceptable because of religious beliefs. As a footnote, there are landless people in rural Myanmar who make their living as rat-hunters; they sell rats for human consumption. On some occasions they are employed by villagers to capture rodents in and around their stores and fields.

There are always challenges to develop pest management systems that can be adaptable and feasible for farmers to apply. Social dimension plays an important role in developing the adoption pathways for broad-scale rodent management approaches.

Future directions for developing village ecologically based rodent management (EBRM) in Myanmar for grain store include:

- Build capacity and strengthen local champions.
- Be aware of the social dimension in different regions that may constrain farmers from following all of the management recommendations.
- Build knowledge on the biology (population and breeding ecology and spatial behaviour) of the target species.
- Develop a farmer participatory approach for different crops and different agroecosystems in Myanmar.

There was an average of 45% reduction in rodent damage to rice when rodent control was undertaken in rice stores in Myanmar (Fig. 1).

6.2 Case study 2: rural community rodent management in Tanzania

The study was conducted in rural communities in Tanzania in order to examine rodent damage loss and contamination in stored maize in smallholder farms in East Africa (Mdangi et al., 2013). Different novel techniques for assessing rodent damage, namely open and closed structures (cribs and sacks), were employed in a treatment-control trial design replicated across different households and hamlets within the Berega community of central Tanzania. Six farmers were selected randomly, each from five different hamlets. Three farmers used the sacks to store their maize, while the other three used cribs. Before the maize was placed in bags and cribs, it was treated with an insecticide (Actellic Super Dust, manufactured by Syngenta) according to the instructions on the package to prevent insect damage.

Sampling of maize was conducted every month for 7 months. In each month, sampling from each replicate was done using a 0.25-kg container of maize (n = 4), making a total of 1 kg of maize seeds. These samples were taken from the middle and the periphery from each storage structure. Damaged and undamaged seeds were counted and weighed, and the percentage of grain damage and the amount of weight loss were calculated. Similarly, samples taken each month were also used to assess the level of contamination and number of rodent droppings.

To determine the rodent species and population abundance in the households, five farmers from five different hamlets were randomly selected. Equal numbers of live-traps (five locally made traps and five Sherman live-traps) were baited with peanut butter and were placed against walls and in the corners of the house. Trapped animals were identified to species level following the guidelines given in Kingdon (1997).

The results from this study showed significant correlations between the monthly rates of rodent-damaged maize seeds, maize weight loss and the number of rodent droppings (Mdangi et al., 2016). Similarly, significant differences were observed for damage, loss and contamination between different storage structures (open and closed cribs and sacks). The mean monthly rate of damage was 40.4%, 7.9%, 17.7% and 0% in open cribs, closed cribs, open sacks and closed sacks, respectively.

These findings suggest that reducing rodent infestation through the use of improved storage structures could lead to major savings in the amount and quality of stored cereals available to households, thus increasing food security.

Future research directions for rodents and post-harvest losses in Tanzania include conducting more research on the factors influencing these losses, because there is a scarcity of documented information available. There are many technologies which smallholder farmers are using to protect their produce, but most are yet to be evaluated and documented.

7 Conclusion

Based on a handful of studies in Asia and eastern Africa over the past decade, we now know more about the type and level of post-harvest damage and losses caused by rodents to cereal staples, but further work is required to study the ecology of the different pest species under different situations. The species causing damage and the level of losses or damage caused by rodents to post-harvest grain stores in Latin America also needs to be a focus of research.

More research is required to address questions such as: Where do the rodents nest? How far do they range in their daily and seasonal movements?

When do they breed? These are just some of the research questions to be asked.

Recent research in the developing countries has demonstrated that the losses caused by rodents can be reduced (see previous case studies). Improving rodent management strategies reduces damage and losses. If losses were reduced by half from around 10% to 5%, that would be a significant increase in the amount of grain available for human consumption. This would be especially important for the food security of smallholder farming households. It is virtually impossible to be free from rodents, but their impact can be greatly reduced.

8 Future trends in research

There is now a greater understanding of the impacts of rodents on cereals in grain stores, but there are still many gaps in our knowledge. More research needs to be conducted on the ecology of rodents in and around grain stores. Several questions remain:

- Which are the key pest species?
- Are the species different from those that occur in the neighbouring fields, or do they simply follow where the cereal is accumulated?
- Where do they nest and breed?
- How far do they move?
- How do they access grain stores?
- What control strategies work best?
- Can management methods take advantage of the "landscape of fear" that influences the movement of rodents around the agricultural landscape (see Krijger et al., 2017)?

There is ongoing work to identify new types of rodenticides, but many of these are still some years away. Making the most of currently available strategies remains the best approach. A combination of methods is recommended (see Section 5). There is research work looking at developing fertility control agents, but these will likely work best in combination with other management methods.

A rapidly expanding field of detection and reporting systems is becoming available. Some devices include passive infra-red motion detectors, which are placed in a box similar in design to a bait station, to detect the presence and/or activity of rodents. The device then sends alerts to mobile or smart phones via an app. This can then be used to trigger some management intervention or be used to confirm that the activity has declined after intervention. Monitoring the effectiveness of management is always important, and such systems will be more readily available in the future.

Sample of rice grain from a rice store in Laos. Note the faeces mixed in with the rice grain. Photo: Alex McWilliam (CSIRO)

Rice grain stored in a grain store, Laos. The rodent faeces are easily seen. Photo: Alex McWilliam (CSIRO)

Typical grain store within a rural village, Laos. Note the metal sleeves to try and prevent access by rats. The grain is stored loosely in the woven bamboo structure. Photo: Alex McWilliam (CSIRO)

Typical grain store within a rural village, Laos. Note the wide 'rat guards' at the top of the posts to try and prevent access by rats. The grain is stored loosely in the woven bamboo structure. Photo: Alex McWilliam (CSIRO)

Rodent damage to maize kernels. Note the gnawing of the kernels to remove the germ. Photo: Steven Belmain (NRI)

Rodent damage to maize cobs, Tanzania. Photo: Steven Belmain (NRI)

Maize drying crib, Tanzania. Photo: Steven Belmain (NRI)

Grain storage in Africa. Photo: Steven Belmain (NRI)

Untidy grain storage, Bangladesh (prior to intervention). Photo: Steven Belmain (NRI)

Tidy grain storage, Bangladesh (after intervention). Note the metal flashing on the legs and the metal cover over the top of the grain store. Photo: Steven Belmain (NRI)

9 Where to look for further information

There are only a few resources available specifically for managing rodents in grain stores.

- The second edition of Buckle and Smith's (2015) *Rodent Pests and Their Control* contains a chapter by Lund (2015) which summarised impacts by rodents.
- The *Encyclopedia of Pest Management* (Cao et al., 2002) often summarises what is known about post-harvest impacts, but this tends to be only in summary form.
- The EcoRodMan website (https://ecorodman.nri.org/) provides some current information about the ongoing studies looking at rodent damage to stored grains and provides some results of recent trials of storage systems.

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