Crop Protection 145 (2021) 105638

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Small mammal communities, associated damage to rice and damage prevention in smallholder rice storage facilities in Sri Lanka

Nyo Me Htwe[a,1], Siriwardana Rampalage Sarathchandra[b,1], Vincent Sluydts[c,d], Lionel Nugaliyadde[e], Grant R. Singleton[f,g], Jens Jacob[d,*]

[a] Plant Protection Division, Department of Agriculture, Bayintnaug Rd, Gyogone, Insein Township, Yangon, Myanmar
[b] Rice Research and Development Institute, Batalagoda, Ibbagamuwa, Kurunegala, Sri Lanka
[c] University of Antwerp, Department of Biology, 2610, Wilrijk, Belgium
[d] Julius Kühn-Institute, Institute for Plant Protection in Horticulture and Forests, Vertebrate Research, Toppheideweg 88, 48161, Münster, Germany
[e] Postgraduate Institute of Agriculture, P.O. Box 55, Old Galaha Road, Peradeniya, Sri Lanka
[f] International Rice Research Institute, Los Baños, Laguna, 4031, Philippines
[g] Natural Resources Institute, University of Greenwich, Chatham, Kent ME4 4TB, United Kingdom

A R T I C L E I N F O

Keywords:
Food security
Pest rodents
Post-harvest
Rice production
Rodent management
Sri Lanka

A B S T R A C T

Several rodent species damage rice crops and commensal rodents cause damage to stored produce and infrastructure, hygienic problems and they can transmit zoonotic pathogens. In the first such study in Sri Lanka, we identified the main rodent and shrew species and the extent of post-harvest damage caused in rice storage facilities of smallholder farmers. Netting of rice bags was trialled as a new measure of protection. Field experiments were performed in the three main agro-ecological zones of Sri Lanka.

Five rodent species and one shrew species were captured in storage facilities. *Rattus rattus*, *Bandicota indica* and *Suncus murinus* were the dominant species in storage facilities. The small mammal composition was more related to season than to region. In storage, depending on region, 3.2–9.1% (mean 7.6%) of rice was lost to rodents when rice was stored indoors in unprotected polyethylene bags. Netting around bags reduced damage by 89% - equivalent to the annual rice consumption of one person per storage facility, reduced the presence of rodent droppings by 92% and the bag area damaged by rodents by 96%.

Our findings clearly show the considerable amount of damage caused by rodents to rice post-harvest across three agro-ecological zones of Sri Lanka and indicate that netting bags considerably reduces damage and contamination. This netting can be used to aid the development of an ecologically-based rodent management (EBRM) program tailored to local conditions. More detailed studies are needed to fully understand the population and breeding ecology of the relevant rodent pest species in relation to damage patterns to optimize management beyond individual structural measures.

1. Introduction

Net cereal production needs to be increased by 50% from 2000 to 2050 to satisfy the food requirements of the growing global population (World Bank, 2007), especially in Asia where 578 million people are undernourished (UN, 2011). This entails strategies not only to increase productivity but also to minimize losses. Rice is the staple food across Asia (World Bank, 2007) and therefore, highly relevant for food security.

In Asia, rodents are a major agricultural pest that inflicts substantial loss pre- and post-harvest (John, 2014; Singleton et al., 2010). Pre-harvest damage to rice crops is well documented and there are methods to considerably minimize loss (Brown et al., 2017). Mean losses caused by rodents in rice fields typically range from 5 to 15% but can be much higher in individual fields (Brown et al., 2017). Management approaches are often aligned to the principles of ecologically-based rodent management (EBRM) (Singleton et al., 2003). EBRM includes a suite of techniques based on sound knowledge of the target rodent species as well as ecological, social and economic aspects.

The knowledgebase is much thinner for post-harvest losses in stored rice. Stored rice is not only eaten by rodents but also contaminated by

* Corresponding author.
E-mail address: jens.jacob@julius-kuehn.de (J. Jacob).
[1] Authors contributed equally (shared first authorship).

https://doi.org/10.1016/j.cropro.2021.105638
Received 22 January 2021; Received in revised form 18 March 2021; Accepted 22 March 2021
Available online 27 March 2021

rodent feces, urine and hair (Dubock, 1978; Stejskal and Aulický, 2014). It is assumed that post-harvest losses are higher than pre-harvest losses (Parshad, 1999) but there are few systematically collected data available. The scarce information at hand indicates losses in the range of 4–14% in Myanmar (Htwe et al., 2017), 10% in Laos (Brown et al., 2013) and highly variable values in Bangladesh (Belmain et al., 2015; Krijger et al., 2020). The damage level seems to depend on factors including the quality of the structure of the storage facility, maintenance of the surrounding of storage facilities and the rodent community present (Brown et al., 2017, 2020). The latter is often not well documented and may differ considerably from the rodent species present in rice fields. Species usually present in rice storage facilities in SE-Asia include *Rattus* species from the *R. rattus* complex in Laos; *R. rattus*, *R. exulans*, *Bandicota indica* and *B. bengalensis* in Myanmar, and *B. bengalensis* and *Mus musculus* in Bangladesh (Belmain et al., 2015; Htwe et al., 2017; Krijger et al., 2020) and reviewed in Brown et al. (2020).

The mean cropping area of smallholder farmers in Sri Lanka is < 2 ha (http://www.agrimin.gov.lk/web/index.php/home-1/12-project/841-agriculture-sector-modernization-project accessed March 19, 2021). In their rice storage facilities, which are often attached or in close proximity to the houses where farmers' families live, close contact between rodents and people is likely to increase the risk of transmission of rodent borne pathogens to humans and livestock. In Sri Lanka, such pathogens include *Leptospira* species that can cause deadly disease in humans (Nisansala et al., 2019).

Anecdotal evidence suggests that rodent damage in storage facilities is a chronic and serious problem of rice cultivation in Sri Lanka in various locations. The losses hamper food security and, therefore, advice on rodent management is urgently required. However, for Sri Lanka, there is little published about the rodent species present in rice storage facilities of farmers, and, to our knowledge, nothing on the amount of damage caused by rodents in storage. There is one publication that mentioned that *B. bengalensis* has the highest potential to damage rice in Sri Lanka (Prakash, 1988).

Without thorough knowledge of the composition of small mammal species in storage facilities and of the extent of damage caused, there is a weak foundation to develop evidence-based management strategies. Measures need to be aligned to the pest species present to identify the optimal timing to intercept immigration to fields or to storage facilities. Suitable and effective management is required to reduce damage and to determine if the extent of damage justifies the cost of specific actions.

In this study, we identified the small mammal species composition in storage facilities based on systematic trapping and estimated related damage to rice in typical smallholder storage facilities in the three main agro-ecological zones in Sri Lanka. The latter included a trial to use netting to prevent small mammals from consuming stored rice. The findings will aid the development of management tools that can help to improve food security by reducing post-harvest rodent damage and possibly to mitigate the risks of rodent zoonoses for rice farmers in Sri Lanka.

2. Material and methods

2.1. Study sites

This study was conducted in three agro-ecological zones in Sri Lanka: wet zone (Pasyala in Gampaha district; N7 9′0.742’’; E80 8′14.006″), intermediate zone (Kahapathwala in Kurunegala district; N7 23′43.318’’; E80 28′27.04″) and dry zone (Sinhapura in Polonnaruwa district; N8 1′17.976’’; E81 1′19.091″) with annual rainfall >2,500, 2500–1750 and < 1750 mm, respectively (Fig. 1). In Sri Lanka, there are two cultivation seasons namely Maha and Yala, which are synonymous with two monsoon seasons. Maha season is during "north-east (NE) monsoon" from September to March in the following year. Yala season is during "south-west (SW) monsoon" from May to the end of August. We refer to "NE monsoon season" for Maha and "SW monsoon season" for Yala season. The period between the monsoon seasons is referred to as "dry season".

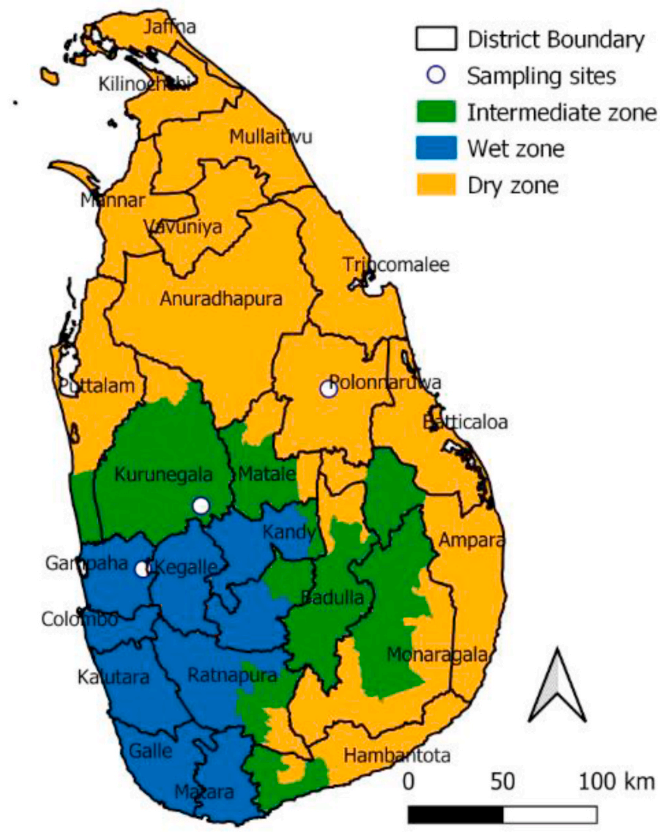

Fig. 1. Agro-ecological zones in Sri Lanka where field work was conducted in smallholder rice storage facilities (map shape based on: https://openi.nlm.nih.gov/detailedresult?img=PMC3943480_1475-2875-13-59-1&req=4 accessed January 19, 2021).

2.2. Small mammal species composition in storage facilities

During 2018 and 2019, snap traps were set in 10 smallholder storage facilities in the wet, intermediate, and dry zone. Ten single capture plastic snap traps (Kness, big-snap-E rat trap) baited with unhulled rice and roasted coconut were set along potential runways in and around each storage facility. Traps were set in the evening and checked the following morning for three consecutive nights in several trapping sessions until at least 50 small mammals were caught per zone per year.

Trapped small mammals were mainly morphologically identified based on the key in Aplin et al. (2003). Occasionally, this was supplemented by phylogenetic analysis of a partial fragment of the *cytochrome b* gene (Nicolas et al., 2012). The percentage of small mammal species per agro-ecological zone and season was calculated as means at the level storage facility and compared among zones and seasons by cluster analysis (complete cluster where the dissimilarity between two clusters is based on the maximum of all possible distances between the cases in these clusters using standardized data) in program JMP (Version 15, 2019 SAS Institute).

2.3. Post-harvest damage to rice

The storage facilities of seven smallholder farmers were selected randomly in each zone. Storage facilities were at least 200 m apart. Twenty rice bags were placed in each farmer's storage facility; 10 control bags (polyethylene bag stored as per farmers' typical storage situation) and 10 treatment bags (polyethylene bag enclosed in fish net with mesh size of 1.5 × 1.5 cm double layer to exclude rodents) (Fig. 2). No rat guards were placed on the legs of the platform of the storage facility that raised the structure 4–5 cm above the concrete floor to be consistent with the usual storage practice in the region.

Twenty kg of rice were placed in each of the control and treatment bags that were stacked and kept in the storage facility in 5 × 4 layers for four months. The position of control and treatment bags was assigned randomly. There were spaces between bags of 8 cm in order to allow rodents to access all bags. Five control and five treatment bags were individually labelled to be checked for damage at the end of the trial in the dry zone. In the wet and intermediate zone, all 20 bags were assessed. Moisture content of grain was measured at the start and end of the storage period using a digital grain moisture meter (KETT Grain moisture meter f523, Symbex International, Dakha, Bangladesh). The size of the bag area damaged by rodents was measured in cm^2 with a ruler. The weight of the grain was measured with a scale to the nearest gram to quantify grain loss. Weight loss of control and treated bags was calculated using the following formulae to calculate the loss caused by rodents:

Moisture loss = (initial weight-final weight)/ initial weight

Adjusted weight = (final weight × (average moisture loss/100)) + final weight

Rodent loss = initial weight – adjusted weight.

In the wet and intermediate zone, the number of rodent droppings in

Fig. 2. Polyethylene bag used for the assessment of post-harvest rodent damage to stored rice. Treatment bags were enclosed in fishnet with mesh size of 1.5 × 1.5 cm double layer to protect rice grain from rodent damage. Control bags were without fishnet (not shown).

a 500 g sample of rice from each bag was counted and upscaled to 20 kg.

A generalized linear mixed model (GLMM) was used to compare the effects of rice losses, the area of holes gnawed by rodents into bags and the number of rat droppings (all ln-transformed) between treatment and control bags and rainfall zones (fixed covariates), accounting for local differences between farms by including farm nested within region as a random effect. All three response variables were modelled with a Gaussian residual distribution. Restricted maximum likelihood estimation (REML) was performed in program JMP (Version 15, 2019 SAS Institute) to obtain parameter estimates and associated probabilities. Degrees of freedom for inference statistics were approximated using Satterthwaite's method. Visual inspection of the residuals indicated model assumptions were met.

Correlation coefficients and associated error probabilities were estimated with REML to test for the relationship between the extent of rice loss and the bag area damaged by rodents, the extent of rice loss and the number of rodent droppings per bag, and the bag area damaged by rodents and the number of rodent droppings per bag.

Mean values are reported with standard errors throughout.

3. Results

3.1. Small mammal species composition in storage facilities

In the storage facilities, the most common species at all agro-ecological zones in all seasons were *R. rattus*, *Bandicota indica* and the mainly insectivorous small mammal *Suncus murinus* (Table 1). *R. exulans* was rare (1% of total number) and did not occur in the intermediate zone. *Mus booduga* was trapped only in the wet zone while *B. bengalensis* was trapped only in the intermediate zone.

The hierarchical cluster indicated that species composition (percentage of species per agro-ecological zone and season) was more affected by season than by agro-ecological zone (Fig. 3) because dry seasons and monsoon seasons clustered more closely together than the three agro-ecological zones.

3.2. Post-harvest damage to rice

During four months of storage, there was a decrease in rice weight in both treated and control bags. Mean weight loss adjusted for moisture in unprotected control bags (1.53 ± 0.17 kg) was 9-fold higher than in treatment bags that were covered with netting (0.17 ± 0.08 kg) ($p < 0.001$, df = 330, t = 7.21; Tukey post-hoc test). Average loss in the dry zone (0.64 ± 0.17 kg) was about a third of the loss in the wet (1.83 ± 0.35 kg) (p = 0.0054, df = 34, t = 2.97) and intermediate zones (1.68 ± 0.14 kg) (p = 0.012, df = 34, t = 2.62) (Fig. 4a). There was no effect of the interaction of treatment and region on rice loss (p = 0.21, $F_{2,330}$, F = 1.59).

The mean size of holes gnawed by rodents into unprotected control bags was 15.9 ± 1.6 cm^2, which was about 26-fold larger than for treatment bags (0.6 ± 0.3 cm^2) ($p < 0.001$, df = 344, t = 9.76) (Fig. 4b). There was no effect of region (p = 0.54, $F_{2,344}$ = 0.623) or of the interaction of treatment and region (p = 0.35, $F_{2,344}$ = 1.067) on mean size of holes gnawed by rodents into rice bags.

At the end of the study, the average number of rodent droppings per 20 kg control bag was 66.3 ± 7.8, which was about 13-fold larger than for treatment bags (5.1 ± 2.1) ($p < 0.001$, df = 276, t = 7.69) (Fig. 4c). There was no effect of region or of the interaction of treatment and region (p = 0.671, $F_{1,276}$, F = 0.181) on the number of rodent droppings in rice bags (p = 0.677, $F_{1,276}$, F = 0.174).

There were close positive correlations between the extent of rice loss and the bag area damaged by rodents (r = 0.68; $p < 0.001$; n = 42) as well as between the extent of rice loss and the number of rodent droppings per bag (r = 0.61; $p < 0.001$; n = 28). There was a positive correlation between the bag area damaged by rodents and the number of rodent droppings per bag (r = 0.93; $p < 0.001$; n = 28).

Table 1
Species composition of small mammals trapped in and around smallholder rice storage facilities in three agro-ecological zones of Sri Lanka (n – number of smallholder rice storage facilities sampled).

Agro-ecological zone	Season	Species composition % (standard error)					
		Rattus rattus	Rattus exulans	Bandicota indica	Bandicota bengalensis	Mus booduga	Suncus murinus
	dry n = 10	97.5 (2.4)	0.0 (0.0)	2.5 (2.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Wet	NE monsoon n = 10	81.5 (3.8)	2.1 (1.4)	4.5 (2.2)	0.0 (0.0)	0.0 (0.0)	12.0 (3)
	SW monsoon n = 10	85.9 (3.6)	0.0 (0.0)	2.5 (1.8)	0.0 (0.0)	4.4 (2.3)	7.2 (2.1)
	dry n = 8	100 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Inter-mediate	NE monsoon n = 10	86.3 (4.7)	0.0 (0.0)	1.4 (1.4)	0.0 (0.0)	0.0 (0.0)	12.3 (4.9)
	SW monsoon n = 10	88.5 (2.9)	0.0 (0.0)	1.8 (1.1)	1.3 (1.2)	0.0 (0.0)	8.5 (2.0)
Dry	SW monsoon n = 10	86.3 (2.0)	3.3 (2.2)	0.7 (0.7)	0.0 (0.0)	0.0 (0.0)	9.7 (2.4)

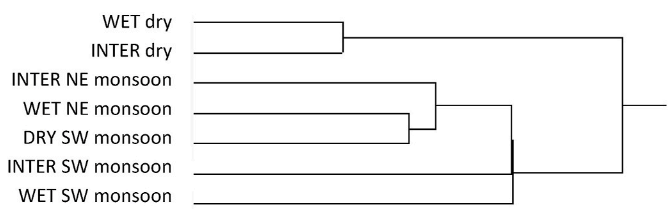

Fig. 3. Hierarchical cluster analysis for small mammal species composition in Sri Lanka by agro-ecological zone (WET, DRY, INTERMEDIATE) during north-east (NE) monsoon, south-west (SW) monsoon and dry season.

4. Discussion

This is the first description of the species composition of and damage by rodents in smallholder rice storage facilities in Sri Lanka and one of the few systematic studies of this topic in south Asia. *R. rattus*, *S. murinus* and *B. indica* were the main species in and around storage facilities. *S. murinus* was present regularly – an invasive insectivorous species distributed throughout south Asia and considered a pest because it damages a wide variety of stored foods (Seymour et al., 2005). This small mammal composition was similar to the suite of pest species in Bangladeshi rice storage facilities (Belmain et al., 2015; Krijger et al., 2020). *R. rattus* was the most common rodent pest across the three agro-ecological zones and most likely the species causing most damage to stored rice.

The small mammal species composition in rice storage facilities seemed more related to season than to agro-ecological zone. This indicates the importance of seasonal weather variability across the island of Sri Lanka – especially rainfall – as a direct and/or indirect driver of infestation with small mammals in smallholder rice storage facilities. Rodent activity can depend on weather conditions (Uria et al., 2013; Vickery and Bider, 1981) as can population dynamics driven by food availability (Andreassen et al., 2020) synchronized by cropping seasons (Htwe et al., 2012) or other resources that are regulated by weather (Heisler et al., 2014; Imholt et al., 2011; Krebs et al., 2004). If there is a strong relation of rainfall and pest rodents accessing rice storage facilities, rainfall could be used in the future to predict rodent infestation in storage to take early action.

Other studies reported different species compositions in rice storage facilities and field crops in south Asia and southeast Asia (Brown et al., 2017; Htwe et al., 2017) demonstrating the need for different rodent management approaches in rice fields *versus* storage facilities. So far, not much is known about the composition of the small mammal community in rice fields in Sri Lanka – this is an area for future work. Seventeen rodent species were reported in a Sri Lanka-wide survey of mainly non-agricultural habitats (Niroshini and Meegaskumbura, 2014) including the species detected in this study. No endemic species occurred in the storage facilities but they might be present in adjacent natural habitats. Rodent management strategies need to balance the need to maintain the endemic species whilst managing the key pest species (Stuart et al., 2007) but this is only possible when species distributions are known.

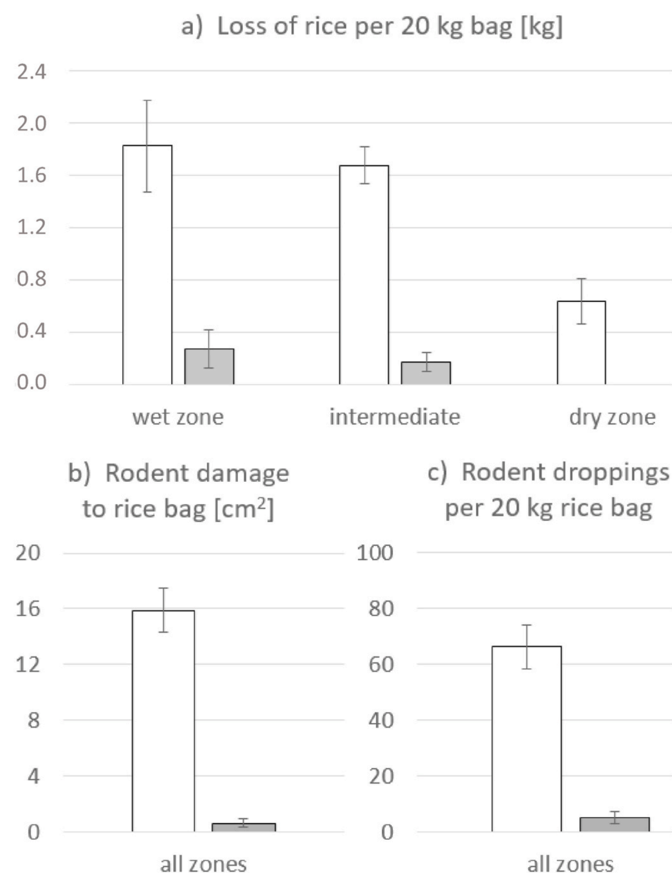

Fig. 4. a) rice losses in smallholder storage facilities due to rodents in three agro-ecological zones of Sri Lanka (wet, dry and intermediate zone), b) area of damage to rice bags caused by rodents in three agro-ecological zones of Sri Lanka and c) droppings of rodents in rice bags in two agro-ecological zones of Sri Lanka (wet and intermediate zone). Bags were either without (open columns) or with protective netting to protect bags from rodent damage (grey columns). Values are means of values from seven replicate storage facilities per zone ±standard error.

The mean post-harvest loss during storage caused by rodents to rice of 7.6% was intermediate compared to findings in other rice systems in Asia (Belmain et al., 2015; Brown et al., 2013). Given farmers in our study stored on average 1600 kg of rice, the loss was about 110 kg in a 4-month period. This is very similar to the loss reported from storage facilities in Laos (Brown et al., 2013) and in the range of the values known from Bangladesh and Myanmar (Belmain et al., 2015; Krijger et al., 2020). Based on the annual per capita rice consumption of 107 kg in Sri Lanka (Galappattige, 2019) the loss caused by rodents post-harvest in a regular smallholder storage facility equates to feeding a person for one year. This suggests that post-harvest losses have a highly important impact on food security of Sri Lanka. Research on post-harvest losses to maize in eastern Africa also highlight the importance of effective post-harvest management of cereals to improve the food security of smallholder farmers (Huss et al., 2020; Mdangi et al., 2013).

Post-harvest rodent damage was considerable and suitable measures for loss reduction could provide many more meals to smallholder farmer households. Several methods are available to reduce the post-harvest impact of rodents including regular kill-trapping, improved sanitation in and around storage facilities, and constructing rodent-proof grain stores (Belmain et al., 2015; Brown et al., 2020; Mdangi et al., 2013). The latter can be costly in the short term but provides long-term benefit. The level of hygiene in and around houses influences rodent population densities (Htwe et al., 2017). Brown et al. (2020) recommend that at least 20–30 m around storage facilities be cleaned to minimize rodent infestation, which requires regular labour-intense action. Farmer interviews during field visits indicated that rice farmers in Sri Lanka do not tend to kill rodents in and around their houses, partially because of religious beliefs. Therefore, the simple technique of netting rice bags may be a suitable method to manage rodent losses. A survey of the attitudes and practices of farmers is required to validate large-scale acceptance of this management approach. This should include a trial where all bags in storage are either equipped with netting or have no netting to check for no-choice effects and ideally would be conducted across a range of pest rodent population abundances.

Covering polythene bags with fishnets was adequate to prevent rodent losses and damage to bags as well as contamination of bags almost completely. Netting decreased rice loss in an average Sri Lankan smallholder rice storage facility by 89% (gain of approximately 109 kg of rice equal to an amount of 725 rice meals of 150 g) in a four-month period. The use of netting to prevent rice loss in storage was more efficient than intervention by trapping and improved general farm hygiene that reduced rice losses in Myanmar and Bangladesh by 30% and 80%, respectively (Belmain et al., 2015).

Similar to rice loss, there was a more pronounced treatment effect on the number of rodent droppings in rice in this study compared to the effects reported for a comparable storage duration from Bangladesh (Belmain et al., 2015). The density of rodent droppings in stored rice in the current study was >30 times lower when rice was stored in bags in this study than in Bangladesh where rice was stored in baskets (Belmain et al., 2015), and also was considerably lower than in a study in Laos where rice was kept in raised grain stores without bags (Brown et al., 2013).

The close positive correlations among rice losses, rodent damage to bags and the number of rodent droppings in the bags indicate that it was indeed mostly rodents (and possibly *S. murinus*) and not insects causing damage. When rodents manage to gnaw through the bag they do consume and contaminate rice in the bags suggesting that suitable intervention can offer multiple advantages regarding food security and health protection through netting. The cost for netting a 20 kg bag of circa $US 0.40 equals the value of 2 kg of stored rice (https://pmb.gov.lk/index.php?lang=en accessed January 19, 2021). Given these numbers and an annual income of $US 838 per hectare (Socio Economics and Planning Centre, 2019) the additional cost of storing rice seems appropriate. However, the method may not be sufficient if rodent pressure is higher than experienced in this study. Rodent damage to protected bags may be higher when no unprotected bags are available to rodents. This requires further study.

The use of non-chemical rodent control measures is intended to minimize pest rodent population abundance and associated damage. Low rodent abundance and limited access for rodents to stored rice will not only improve rice production but may also mitigate other problems caused by rodents including social issues (John, 2014). In addition, environmental issues related to the use of rodenticides (van den Brink et al., 2018) and other compounds to reduce rodent-related health risks (Hinds et al., 2021; Jacob et al., 2021) could be mitigated. Several zoonotic pathogens that are present in Sri Lankan rodents and their ectoparasites (Böge et al., 2021; Gamage et al., 2017) pose serious health risks to people and livestock that should be managed. Hence, rodent control should have high priority for farmers, agricultural and health authorities to improve livelihoods and environmental safety alike.

In many developing countries across the world, storage conditions for agricultural produce including rice are inadequate (Huss et al., 2020; Proctor, 1994). Therefore, the findings of this study may be useful to increased food availability in countries beyond Sri Lanka and beyond the storage of rice.

5. Conclusions

Several species of small mammals inhabit storage facilities in three agro-ecological zones in dry and monsoon seasons across Sri Lanka. They cause considerable damage to stored rice. The losses clearly justify action to enhance food security and effective rodent management also is required to protect the health of humans and livestock from rodent-borne pathogens. At the infestation present in this study, losses and contamination of stored rice can be substantially reduced by covering rice bags with a double layer of fish net with mesh size of 1.5 × 1.5 cm. The population and breeding ecology of the relevant rodent species and other relevant aspects need to be studied in more detail to develop and field test a suitable EBRM approach for the Sri Lankan agro-ecological zones that combine post-harvest and pre-harvest crop protection. This should consider the Buddhist culture where killing mammals is usually not tolerated. The development of tailor-suited strategies to improve the control of rodents is worthy of further support given their considerable positive impact on the food security of smallholder farmer families in Sri Lanka and other regions such as southeast Asia (see Brown et al., 2020) and eastern Africa (Mdangi et al., 2013).

Role of funding source

The funding sources had no involvement in study design, data collection and analyses, interpretation of data, writing the manuscript and the decision to submit the article for publication.

CRediT authorship contribution statement

Nyo Me Htwe: Conceptualization, Methodology, data collection, Data curation, data, Formal analysis, Writing – original draft, all: writing manuscript draft, Supervision, Validation, all: reviewing, Writing – review & editing. **Siriwardana Rampalage Sarathchandra:** data collection, Data curation, Validation, all: reviewing, Writing – review & editing. **Vincent Sluydts:** Data curation, data, Formal analysis, Writing – original draft, all: writing manuscript draft. **Lionel Nugaliyadde:** Supervision. **Grant R. Singleton:** Supervision. **Jens Jacob:** Conceptualization, Methodology, Data curation, data, Formal analysis, Writing – original draft, all: writing manuscript draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Rice Research Development Institute (RRDI) researchers and extension staff of the provincial and inter-provincial Department of Agriculture in Sri Lanka for help in data collection. Special thanks go to Sri Lankan farmers who assisted in our fieldwork despite of their reluctance to see small mammals sacrificed. The study was jointly funded by the German Federal Ministry of Education and Research (project Rat-Adapt FKZ 01DP17063) awarded to JJ, and the Swiss Agency for Development and Cooperation funded Closing Rice Yield Gaps in Asia with Reduced Environmental Footprint (CORIGAP) project (grant# 81046615). We thank the International Rice Research Institute in the Philippines, the Rice Research Development Institute in Sri Lanka, the Department of Agriculture, Myanmar and JKI, Germany for institutional support and encouragement.

References

Andreassen, H.P., Sundell, J., Ecke, F., Halle, S., Haapakoski, M., Henttonen, H., Huitu, O., Jacob, J., Johnsen, K., Koskela, E., 2020. Population cycles and outbreaks of small rodents: ten essential questions we still need to solve. Oecologia 1–22.

Aplin, K.A., Brown, P.R., Jacob, J., Krebs, C.J., Singleton, G.R., 2003. Field Methods for Rodent Studies in Asia and the Indo-Pacific, ACIAR Monograph 100. Australian Centre for International Agricultural Research, Canberra.

Belmain, S.R., Htwe, N.M., Kamal, N.Q., Singleton, G.R., 2015. Estimating rodent losses to stored rice as a means to assess efficacy of rodent management. Wildl. Res. 42, 132–142.

Böge, I., Pfeffer, M., Htwe, N.M., Maw, P.P., Sarathchandra, S.R., Sluydts, V., Piscitelli, A. P., Jacob, J., Obiegala, A., 2021. First detection of *Bartonella spp*. in small mammals from rice storage and processing facilities in Myanmar and Sri Lanka. Microorganisms 9, 658. https://doi.org/10.3390/microorganisms9030658.

Brown, P.R., Douangboupha, B., Htwe, N.M., Jacob, J., Mulungu, L., Nguyen, T.M.P., Singleton, G.R., Stuart, A.M., Sudermaji, 2017. Control of rodent pests in rice cultivation. In: Sasaki, T. (Ed.), Achieving Sustainable Rice Cultivation. Burleigh Dodds Science Publishing, Cambridge, UK, pp. 1–34.

Brown, P.R., McWilliam, A., Khamphoukeo, K., 2013. Post-harvest damage to stored grain by rodents in village environments in Laos. Int. Biodeterior. Biodegrad. 82, 104–109.

Brown, P.R., Singleton, G.R., Belmain, S.R., Htwe, N.M., Mulungu, L.S., Mdangi, M., Cavia, R., 2020. Advances in understanding rodent pests affecting cereal grains. In: Maier, D. (Ed.), Advances in Postharvest Management of Cereals and Grains. Burleigh Dodds Scientific Publishing, Cambridge, UK (in press).

Dubock, A.C., 1978. Rodent control in crop stores. Outlook Agric. 9, 220–224.

Galappattige, A., 2019. Rice Rebounds - Grain and Feed Annual 2019. USDA Foreign Agricultural Service, pp. 1–16.

Gamage, C.D., Yoshimatsu, K., Sarathkumara, Y.D., Kulendiran, T., Nanayakkara, N., Arikawa, J., 2017. Serological evidence of hantavirus infection in Girandurukotte, an area endemic for chronic kidney disease of unknown aetiology (CKDu) in Sri Lanka. Int. J. Infect. Dis. 57, 77–78.

Heisler, L.M., Somers, C.M., Poulin, R.G., 2014. Rodent populations on the northern Great Plains respond to weather variation at a landscape scale. J. Mammal. 95, 82–90.

Hinds, L.A., Grice, D., Watson, D.M., Jacob, J., 2021. Efficacy of a combined insecticide-rodenticide product on ectoparasite and commensal rodent mortality. Pest Manag. Sci. 77 (3), 1160–1168.

Htwe, N.M., Singleton, G.R., Hinds, L.A., Propper, C.R., Sluydts, V., 2012. Breeding ecology of rice field rats, *Rattus argentiventer* and *R. tanezumi* in lowland irrigated rice systems in the Philippines. Agric. Ecosyst. Environ. 161, 39–45.

Htwe, N.M., Singleton, G.R., Maw, P.P., 2017. Post-harvest impacts of rodents in Myanmar; how much rice do they eat and damage? Pest Manag. Sci. 73, 318.

Huss, M., Brander, M., Kassie, M., Ehlert, U., Bernauer, T., 2020. Improved storage mitigates vulnerability to food-supply shocks in smallholder agriculture during the COVID-19 pandemic. Global Food Security 28, 100468.

Imholt, C., Esther, A., Perner, J., Jacob, J., 2011. Identification of weather parameters related to regional population outbreak risk of common voles (*Microtus arvalis*) in eastern Germany. Wildl. Res. 38, 551–559.

Jacob, J., Aplin, K., Watson, D.M., Hinds, L.A., 2021. Assessing the efficacy of oral intake of insecticides on mortality of fleas and ticks on commensal *Rattus* species. J. Pest. Sci. https://doi.org/10.1007/s10340-020-01316-5.

John, A., 2014. Rodent outbreaks and rice pre-harvest losses in Southeast Asia. Food Sec 6, 249–260.

Krebs, C.J., Kenney, A.J., Singleton, G.R., Mutze, G.J., Pech, R.P., Brown, P.R., Davis, S. A., 2004. Can outbreaks of house mice in southeastern Australia be predicted by weather models? Wildl. Res. 31, 465–474.

Krijger, I.M., Gort, G., Belmain, S.R., Koerkamp, P.W., Shafali, R.B., Meerburg, B.G., 2020. Efficacy of management and monitoring methods to prevent post-harvest losses caused by rodents. Animals 10, 1612.

Mdangi, M., Mulungu, L., Massawe, A., Eiseb, S., Tutjavi, V., Kirsten, F., Mahlaba, T., Malebane, P., von Maltitz, E., Monadjem, A., 2013. Assessment of rodent damage to stored maize (*Zea mays* L.) on smallholder farms in Tanzania. Int. J. Pest Manag. 59, 55–62.

Nicolas, V., Schaeffer, B., Missoup, A.D., Kennis, J., Colyn, M., Denys, C., Tatard, C., Cruaud, C., Laredo, C., 2012. Assessment of three mitochondrial genes (16S, Cytb, CO1) for identifying species in the Praomyini tribe (Rodentia: muridae). PloS One 7, 1–11.

Niroshini, D., Meegaskumbura, S., 2014. Identification of Sri Lankan muroid rodents using hair anatomy. Ceylon Journal of Science 43, 17–30.

Nisansala, T., Bandara, K., Weerasekera, M., Gunasekara, C., Marasinghe, C., Gamage, C. D., Fernando, N., Ranasinghe, N., 2019. Manifestations and outcomes of leptospirosis during local outbreaks in high endemic districts of Sri Lanka: a retrospective multi-center study. Asian Pac J Trop Med 12, 442–449.

Parshad, V.R., 1999. Rodent control in India. Integrated Pest Manag. Rev. 4, 97–126.

Prakash, I., 1988. Rodent Pest Management. CRC Press, Boca Raton, Florida.

Proctor, D., 1994. Grain Storage Techniques: Evolution and Trends in Developing Countries. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Seymour, A., Varnham, K., Roy, S., Harris, S., Bhageerutty, L., Church, S., Harris, A., Jennings, N.V., Jones, C., Khadun, A., 2005. Mechanisms underlying the failure of an attempt to eradicate the invasive Asian musk shrew *Suncus murinus* from an island nature reserve. Biol. Conserv. 125, 23–35.

Singleton, G.R., Belmain, S., Brown, P.R., Aplin, K., Htwe, N.M., 2010. Impacts of rodent outbreaks on food security in Asia. Wildl. Res. 37, 355–359.

Singleton, G.R., Hinds, L.A., Krebs, C.J., Spratt, D.M., 2003. Rats, Mice and People: Rodent Biology and Management. Australian Centre for International Agricultural Research, Canberra.

Socio Economics, Planning Centre, 2019. Cost of cultivation of agricultural crops, 2018 yala. Agricultural Economic Study 105, 112.

Stejskal, V., Aulický, R., 2014. Field evidence of roof rat (*Rattus rattus*) faecal contamination of barley grain stored in silos in the Czech Republic. J. Pest. Sci. 87, 117–124.

Stuart, A.M., Prescott, C.V., Singleton, G.R., Joshi, R.C., Sebastian, L.S., 2007. The rodent species of the Ifugao Rice Terraces, Philippines–target or non-target species for management? Int. J. Pest Manag. 53, 139–146.

UN, 2011. The Millennium Development Goals Report 2011. United Nations, New York, p. 72.

Uria, I.T., Mahiques, J.M., Gras, L.M., 2013. Temporal distribution and weather correlates of Norway rat (*Rattus norvegicus*) infestations in the city of Madrid, Spain. EcoHealth 10, 137–144.

van den Brink, N.W., Elliott, J.E., Shore, R.F., Rattner, B.A., 2018. Anticoagulant Rodenticides and Wildlife. Springer, Cham, Cham, Switzerland.

Vickery, W.L., Bider, J.R., 1981. The influence of weather on rodent activity. J. Mammal. 62, 140–145.

World Bank, 2007. World Development Report 2008: Agriculture for Development. The World Bank, Washington, DC, USA, pp. 1–390.