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Abstract

Rodents are a major pest of rice throughout Southeast Asia, causing both pre- and post-harvest losses. In Cambodia, where 90% of the cultivated land is used for rice production, rodent damage to rice can cause significant impacts to smallholder farmers' livelihoods and to food security. To help smallholder farmers minimize yield losses from rodent pests, adaptive research experiments were established in two villages in Takeo province. In each village, three replicate 5-hectare sites were selected for treatment and three for control. In each treatment site, groups of farmers implemented ecologically-based rodent management (EBRM) methods over two rice cropping seasons. The management methods were adapted based on the local situation and preferred practices of farmers and included maintaining basic hygiene in field margins, synchronous planting of rice crops, community rat hunts, no electric fencing and the implementation of a Community Trap Barrier System (CTBS) along with a Linear Trap Barrier System (LTBS) in an area of intensive rice monoculture, and a LTBS with targeted and limited bromadiolone rodenticide in an area growing recession rice on lake margins. Over 130 rats were caught at each treatment site per season and rodent damage levels were reduced from a mean of 22 - 34% per site and season in the non-treatment sites to less than 6% in the treatment sites. Following the implementation of EBRM, rice yields were, on average, 20-32% higher in the treatment sites than in the non-treatment sites, giving a 53 to 169% increase in net income and a benefit-cost ratio ranging from 3:1 to 11:1 per season. We show that rodent damage to rice in Cambodia and the associated yield loss can be significantly reduced following the implementation of cost-efficient EBRM approaches that were locally adapted to village-specific agro-ecological and social conditions. We conclude by discussing incentives that support the adoption of these practices by smallholder farming communities.

1. Introduction

Rodents are a major pest of rice throughout Southeast Asia, causing both pre- and post-harvest losses that can cause devastating impacts to smallholder farmers' livelihoods and to food security (John, 2014; Singleton et al., 2010). In Cambodia, where 90% of the cultivated land is used for rice production, a rice-crop health survey conducted in 2016 recorded a mean of 9% rodent damage across four surveyed provinces, with damage levels of 57% recorded in one of the surveyed fields (Castilla, in press). The infliction of rodent damage to rice from the reproductive stage onwards directly translates into rice yield loss due to the inability of the rice plant to compensate in time for harvest (My Phung et al., 2010; Singleton et al., 2005b). For example, during 1996, Jahn et al. (1999) reported the occurrence of a rodent outbreak in Cambodia which caused a yield loss of 12,600 t of rice; enough to feed more than 50,000 people for a year. The potential for such high crop losses due to rodents necessitates rodent management action. However, in Cambodia, farmers often apply indiscriminate methods such as the acute rodenticide zinc phosphide, abamectin-based insecticides mixed with motor oil, and electric fencing, despite their awareness of the hazardous risks to people and other animals. The efficacies of such methods are also questionable, including the common practice of applying zinc phosphide in tropical agroecosystems (Buckle, 1999; Hoque and Sanchez, 2008).

To develop rodent management strategies that are sustainable and have minimum environmental impact, ecologically-based rodent management (EBRM) strategies are recommended (Singleton et al., 1999a). Through a solid understanding of the species composition and the biology of the pest species, as well as the ecological characteristics of the agro-ecosystem and the local farming and cultural practices, the optimal times, locations and scale of actions can be identified (Brown et al., 1999; Fiedler and Fall, 1994; Leung et al., 1999; Palis et al., 2008). For example, it is known that the breeding seasons for the most important rodent pest species of rice in Southeast Asia are closely linked to rice-cropping cycles due to the abundant availability of food provided by the growing rice crop (Brown et al., 2017). Thus, EBRM strategies for rice ecosystems in this region generally include synchronous planting, community action, and extended fallow periods to reduce pest population build-up. However, an increasing pressure to produce more food with less land and labour availability is leading to intensified cropping frequency and changes to cropping systems that can pose challenges for rodent management.

In Cambodia, the introduction of faster maturing varieties and improvements in irrigation infrastructure has enabled an increase in the frequency of rice crops per year, from one wet season crop to two or three crops per year in some areas (Jahn, 1999), and also an expansion of rice crop production to river and lake margins as the floodwaters recede in the dry season (Frost and King, 2003). For example, between 2002 and 2012, the total annual harvested area for rice paddy increased by 50%, from 2 million to 3 million hectares (FAO, 2017). Such conditions increase the availability of food for rodents during the year, which can thereby exacerbate rodent problems to rice crops. The problem is then compounded by the limited knowledge of rice farmers on how best to manage rodents.

One effective EBRM tool for rice-based agroecosystems is the trap barrier system (TBS; Singleton et al., 2003; Singleton et al., 1998). The TBS was originally developed by Lam (1988) as a method to protect an individual farmer's field. However, it has since been adapted to include a trap crop that is planted several weeks before the surrounding crops. This is often known as the Community-TBS (CTBS) due to its ability to protect 8-10 ha surrounding the trap crop (Singleton et al., 2003; Singleton et al., 1998). Another variant of the TBS is to apply it as a linear barrier known as a Linear-TBS (LTBS) to intercept rodent movement into or within agricultural crops. There are currently no published studies that have examined the effectiveness of this method in rice. However, a recent study in maize fields in China found it to be as effective as a CTBS applied with no trap crop (Wang et al., 2017).

In smallholder farming systems, community participation is needed for successful implementation of EBRM (Palis et al., 2008). In Cambodia, King et al. (2003) conducted a study to determine how an adaptive research approach can be applied to promote effective adoption of EBRM at the community level. Involvement of farmers in the decision making process allows them to combine local knowledge and experience with information and technology options offered by researchers. The farmers test options and then decide on how to adapt and integrate them on their farms to suit local agroecological and socioeconomic conditions. Through this adaptive process, the value of both process and technical knowledge of farmers is highlighted, helping to ensure the sustainability of the learning process in communities (King et al., 2003). Such local experimentation has been found to have a learning effect not only for farmers and researchers, but also for other stakeholders such as policy makers and service providers (Flor et al., 2017; Krupnik et al., 2012). The co-production of knowledge is intended to align these stakeholders and enable innovations, such as EBRM (Leeuwis, 2004).

In this paper, we report on two different adaptive research experiments for EBRM in two villages in Takeo province, Cambodia, where high rodent losses were previously reported. The main aim of the study was to determine whether rodent damage could be decreased and rice yields increased following implementation of integrated EBRM approaches that were locally adapted to village-specific agroecological and social conditions. We also conduct an economic assessment to determine the economic viability of each approach for the farmer.

2. Materials and methods

2.1. Study sites

As part of an adaptive participatory research platform, field trials were established in two villages in Takeo province, Cambodia, namely Ro Vieng village in Traeng district (10º87'N 104º77E) and Kandaul village in Batie district (11°19'N 104° 55'E). Rice farming is the primary livelihood in both villages with an average farm size of 1.2 and 1.1 ha, respectively. In Ro Vieng village, year-round irrigation allows for three rice crops per year: a dry season (DS) crop from December to March, the early wet season (EWS) crop from April to July, and the wet season (WS) crop from August to November. In Kandaul village, rice is mostly grown two times a year: the DS crop from December to April and WS crop from June to November. In the DS, a rice crop is gradually sown on the margins of Lake Tonle Bati as the flood waters recede. In the WS, a rainfed rice crop is grown on higher elevated land above the high-water level. The vast majority of this rainfed area lies fallow in the dry season, except for a few fields with irrigation from the lake. The predominant crop establishment method for rice in both villages is manually broadcast wet direct-seeding.

To identify the main rodent pest species, trapping was conducted using kill-traps during the wet season of 2016.

2.2. Field trial design and treatment details

In each village, focus group discussions were conducted with 10-15 farmers to explain the purpose of the project, to determine the rodent situation across the village rice-growing landscape, to determine the preferred rodent management practices of farmers and to select study sites. During the discussion, the farmers were given a selection of potential options for rodent management that they would like to see evaluated in their village. Choices included the Linear Trap Barrier System (LTBS), the Community Trap Barrier System (CTBS) and community-based rodenticide application. The farmers were then asked to individually vote for their preferred rodent management options, and the options with the highest number of votes were selected for the field trials.

In each village, three replicate 5-hectare sites were selected for treatment and three replicate 5-hectare sites were selected for control (i.e. non-treatment). In each treatment site, groups of farmers implemented EBRM methods during two successive rice cropping seasons. The management methods were based on the preferred practices of farmers and adapted to the local situation.

In Ro Vieng village, rodent management actions at each treatment site included a CTBS, along with a 120 m LTBS near a potential rodent refuge habitat (with no rodenticide treatment). The CTBS consisted of 20 m x 20 m plastic barrier with four multiple-capture cage traps (600 x 240 x

240 mm with a 10 x 10 mm mesh-size to catch mice) encompassing a rice crop that was planted 2 to 3 weeks earlier than the surrounding crops (see Singleton et al., 1998). All sites were at least 200 m away from each other because the CTBS trap crop can attract rats from up to 200 m away (Brown et al., 2006; Singleton et al., 2003; Singleton et al., 1998). Each LTBS consisted of a 120 m long plastic barrier placed on one edge of each 5 ha treatment site, facing a potential source habitat for rats, e.g. forest or scrub habitat. The LTBS was constructed similarly to a CTBS and along the rice crop side of the plastic barrier, 5 multiple-capture traps were placed every 20 m, starting 10 m from the edge, with the entrance of the traps facing the potential source habitat. In Ro Vieng, the LTBS was only set up from the maximum tillering stage – a period known for high rat movement into rice crops, and left in the field until harvest 60 days later. The multiple-capture traps were checked every morning and rats were removed and non-target captures were released. If farmers were not able to check the traps the next day, the traps were temporarily removed from the TBS and the holes that normally lead into the traps were blocked. The number of rodents caught and their sex were recorded for each TBS.

In Kandaul village, the rodent management actions at each treatment site included a LTBS with limited and targeted application of bromadiolone rodenticide. Each LTBS consisted of a 120-240 m long plastic barrier placed on one edge of each 5 ha treatment site, facing the rice-cropping area that was recently harvested; towards the recession rice growing area during the WS and towards the rainfed rice growing area during the DS. Along the side of the plastic barrier that had a rice crop, 5-12 multiple capture traps (depending on the length of the barrier) were placed every 20 m, starting 10 m from the edge. During the DS season in Kandaul, the LTBS was set up during the maximum tillering stage. However, during the next season and upon request by the participatory farmers, the LTBS was set up during the crop establishment due to rodent damage being previously experienced during the seedling stage. The traps were checked as above. For the rodenticide treatment, bromadiolone was applied using a 'pulsed baiting' technique (Buckle, 1984, 1999; Dubock, 1982) at the maximum tillering-booting stage during the DS and at the crop establishment and maximum tillering-booting stage during the WS. Bromadiolone is a second generation anticoagulant rodenticide which has a chronic mode of action, unlike the commonly used acute rodenticide zinc phosphide. Due to the delayed symptoms of poisoning, bait shyness does not occur (Greaves, 1982). Because it takes several days for rodents to die after ingesting a lethal dose, a ‘pulsed baiting’ technique was applied. This technique involves the application of relatively small quantities of bait at weekly intervals, allowing rodents that consumed a lethal dose to die before bait is replenished (Buckle, 1984, 1999; Dubock, 1982). The advantages of this technique are that labour is reduced, less bait is needed and smaller quantities of rodenticides enter the environment. During the sowing stage, one 5 g bromadiolone wax bait block was placed every 10 m along major banks throughout each 5 ha treatment site and alongside other habitat bordering the treatment sites, where rats may be nesting. During the maximum tillering-booting stage, two hundred 5 g bait blocks were applied per treatment site, with one bait block evenly placed every 10 m (± 2 m) throughout the 5 ha treatment site, including the field edges. If fields were flooded, the baits were placed on the rice bund. If fields were dry, the baits were placed inside the rice field, 2 m away from the bund to maximize effectiveness. As there was a low non-target risk, bait blocks were simply placed on the ground, on top of a small pile of rice husk. Seven days after application, each bait station was checked and provided with a new bait block if at least half of a bait block had been consumed or was missing. Uneaten baits were left in the field.

In all treatment sites, additional rodent management activities included synchronous planting of rice crops, two community rat hunts during the early stages of the rice cropping season (during land preparation until early tillering); field sanitation (clearing bunds and field edges from weeds) from booting stage until harvest; and trapping using kill-traps every 2-3 weeks (30 traps per site) from the maximum tillering stage to flowering stage using sweet potato as bait. In addition, reducing bund (embankment) size between rice paddies to ≤15 cm wide or

15 cm high to prevent burrowing by rats was recommended and electric fencing and other rodenticide use was discouraged.

Field sites were selected based on the farmers' willingness to participate in the field trials and one farmer per treatment site was requested to lead the implementation of treatments. In the non-treatment sites, farmers followed their usual rodent management practices. For all the field sites, farmers followed their usual practices for crop management, including fertilizer application and non-rodent pest management. Rice varieties grown included IR504 (IR50401-77-2-1-3) and IR66 in Ro Vieng, and IR504, CAR8, Phka Khnei and Kramomyuon in Kandaul. During each season, the same varieties were used at both treatment and control sites within each village.

2.3. Data collection

At each treatment site, lead farmers were recruited to check and maintain the traps and fences. The number of rodents caught per treatment method was recorded daily by these lead farmers.

During the EWS and DS, damage assessments and crop cuts for each treatment and non-treatment site were made in three randomly selected rice field parcels that were located 5 m, 50 m and 100 m from the CTBS in Ro Vieng and LTBS in Kandaul. In each non-treatment site, damage assessments and crop cuts were made in three randomly selected rice field parcels that were located 50 m from each other in Ro Vieng and 5 m, 50 m and 100 m from the edge of the rice growing area (similar to the treatment plot locations) in Kandaul.

To increase the size of the area assessed in the WS, damage assessments and crop cuts were made in three randomly selected rice field parcels that were located 5 m, 75 m and 150 m from the CTBS in Ro Vieng and LTBS in Kandaul in the treatment sites. In each non-treatment site, assessed rice field parcels were located 75 m from each other in Ro Vieng and 5 m, 75 m and 150 m from the edge of the rice growing area (similar to the treatment plot locations) in Kandaul..

The rodent damage assessments were conducted three times over each growing season; at maximum tillering, reproductive (panicle initiation to flowering) and ripening (as close as possible to crop maturity and within two weeks before harvest) crop growth stages. The damage assessments were conducted following a stratified random sampling design (Aplin et al., 2003; Stuart et al., 2014). The sampling area was the first half of the field parcel that is parallel to the TBS or non-rice habitat. This area was then divided into three equally spaced line strata. Within each stratum, a line transect (parallel to the TBS or non-rice habitat) was placed. These were at 5 m from the edge of the field, and at distances from the edge that were 25% and 50% of the field length. Where possible, the transect covered the entire width of the field parcel, starting and ending two meters from the levee on the edge of the field. Assessments were made on eight equally spaced sampling points along each transect and the total number of cut and uncut tillers at each sampling point were counted. Cut tillers included those that were visibly cut by rodents but had regrown. At each sampling point, a 0.01 m^2 quadrat was placed and the cut and uncut tillers within were counted. If the first sampled quadrat within a sampling point had less than 20 tillers, all the cut and uncut tillers of an additional quadrat were counted. In these cases, the additional quadrat was placed immediately adjacent to the one that had been previously assessed.

During the week prior to harvest, yield measurements were taken from three 2.5 × 2 m quadrats, each randomly placed within one of the stratum. The samples were weighed to the nearest gram and the moisture content (%) recorded from three random grain samples per crop cut.

At the end of each cropping season, farmers and researchers discussed what was done, what the outcomes were, and what they wanted to improve from the EBRM trials. These discussions were documented and provided qualitative insights into the findings from the adaptive research.

Using a structured questionnaire, owners of each rice field sampled for crop cuts were interviewed at the end of each season and asked for details of all their crop production practices, including costs and inputs, e.g. seeds, fertilizer, pesticides. Yields estimated from crop cuts were used to complement these data.

2.4. Statistical analysis

Statistical analyses were carried out using Statistical Package for the Social Sciences (SPSS) version 24 (SPSS Inc., Chicago, IL, USA). Repeated measures ANOVA was conducted to compare rodent capture rates between the CTBS, LTBS and kill traps in Ro Vieng village during the reproductive and ripening crop stages. The main factors entered into the model were season and trap type. Pairwise comparisons of main effects were conducted using the Bonferroni test.

Linear mixed models with maximum likelihood estimation were used to analyse differences in cumulative rodent damage (ln transformed) and rice yield between treatments and seasons for each village separately. Fixed effects entered into the model included treatment, season, field site (i.e. as a proxy for distance to CTBS/LTBS), species and all interactions. Treatment and non-treatment sites were entered as random effects.

To analyse the relationship between rodent damage and rice yield, linear regressions were conducted on each village and season combination.

3. Results

3.1. Rodents captured

The majority of species caught were *Rattus argentiventer*. However, *Rattus rattus* species complex, *Bandicota* sp. and *Mus caroli* were also present. Across all three treatment sites in Ro Vieng, a total of 1234 and 914 rodents were caught during the EWS and WS, respectively (Fig. 1). In both seasons, the majority of these were caught in the CTBS and by community hunting. The CTBS was most effective from the reproductive stage onwards, with more rodents caught in the CTBS as compared to the LTBS or kill-traps ($F_{2,639} = 84.3$, $P < 0.001$; Pairwise comparisons of CTBS vs LTBS and CTBS vs kill-traps: $P < 0.001$). Although, because the CTBS was harvested three weeks before the surrounding crop in the WS, the LTBS and kill traps were more effective during the ripening stage in the WS ($F_{2,213} = 96.2$, $P < 0.001$). During the EWS, the CTBS was harvested at the same time as the surrounding crop. There was no difference in the efficacy between the LTBS and kill-traps during the reproductive to ripening crop growth stages (Pairwise comparison: $P > 0.05$).

In Kandaul, a total of 812 and 636 rodents were caught during the DS and WS, respectively. Of which, 50 to 51% were caught in the LTBS and 27 to 30% were caught by community hunting during each respective season. In the DS, the number of rodents trapped by the LTBS was highest during the reproductive stage, whereas there was no clear peak in captures during the WS.

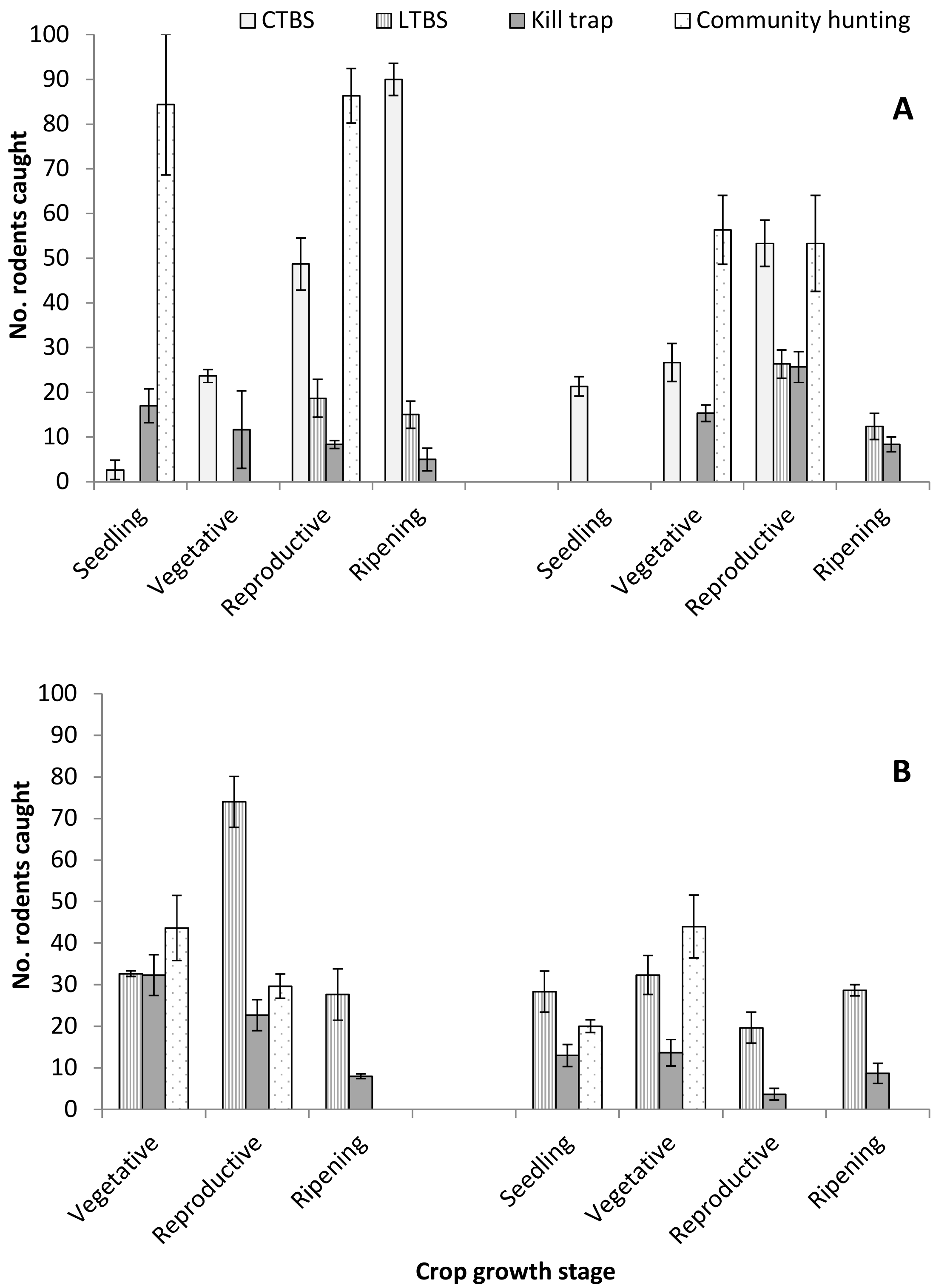

Figure 1. The mean number of rodents caught per treatment site for each method of trapping/hunting across the different crop growth stages during the dry season (DS) or early wet

season (EWS) and wet season (WS) in Ro Vieng (A) and Kandaul (B) villages, Takeo province. Crop growth stages were categorized as seedling, vegetative (early tillering to maximum tillering), reproductive (panicle initiation to flowering) and ripening (milky ripe stage to harvest).

3.2. Impact on rodent damage

In the non-treatment sites, the mean level of rodent damage (calculated as % of cut tillers) per crop stage ranged from 3.8% to 17.9% in Ro Vieng and from 2.6% to 13.1% in Kandaul, whereas, in the treated sites, the mean level of rodent damage per crop stage did not exceed 2.2% (Fig. 2.). Damage was typically highest at the booting and ripening stages, except in the wet season in Kandaul, when it was highest at the maximum tillering stage.

Following the implementation of the EBRM treatments, the cumulative rodent damage, measured from maximum tillering until harvest, was significantly lower in the treated sites as compared to the control sites. In Ro Vieng, the cumulative rodent damage in the treated sites was reduced by 99.1% (from 22.4 to 0.2%) in the EWS and by 86.9 % (from 33.6 to 4.4%) in the WS ($F_{1,36} = 667.6$, $P < 0.001$). In Kandaul, the cumulative rodent damage was reduced by 92.0% (from 30.1 to 2.4%) in the DS and by 83.5% (from 31.0 to 5.1%) in the WS ($F_{1,36} = 237.0$, $P < 0.001$). In Ro Vieng the cumulative damage was higher in the WS ($F_{1,36} = 111.3$, $P < 0.001$) than in the DS. However, the difference between seasons was more pronounced for the treatment sites ($F_{1,36} = 35.3$, $P < 0.001$).

In Ro Vieng, the distance to the CTBS had no effect on yield ($P > 0.05$), whereas in Kandaul, there was a significant three-way interaction between season, treatment and distance to TBS ($F_{2,36} = 3.62$, $P = 0.037$). In the WS, the sites closest to the LTBS, had less damage than those further away, but no distance effect was visible for the DS and the non-treatment sites (Fig. 3.)

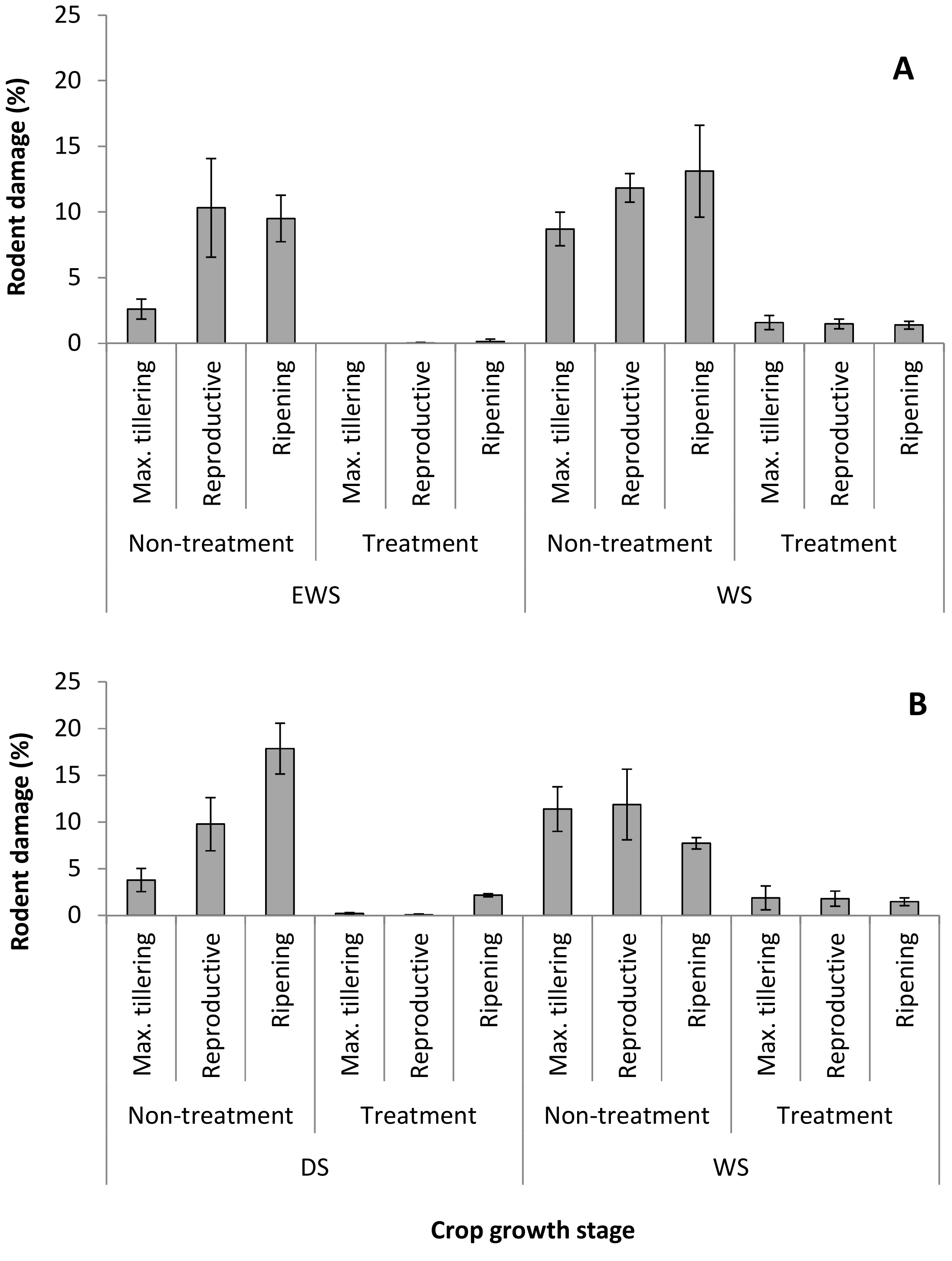

Fig. 2. The mean level of rodent damage per site across the different crop growth stages during the dry season (DS) or early wet season (EWS) and wet season (WS) in Ro Vieng (A) and Kandaul (B) villages, Takeo province.

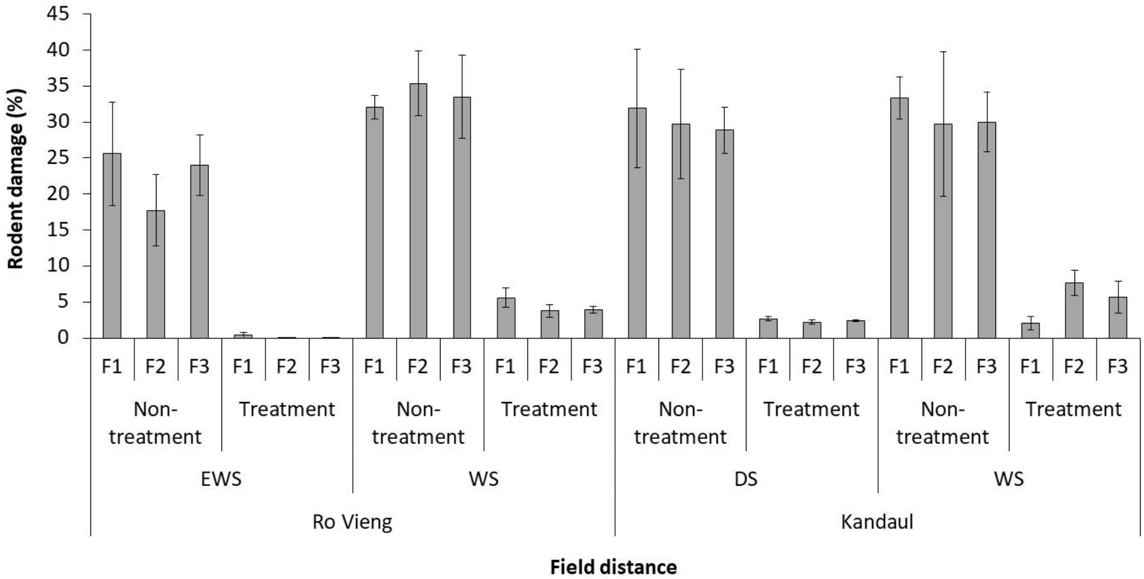

Fig 3. The mean level of rodent damage per site at different distances from the Trap Barrier System(TBS) during the dry season (DS) or early wet season (EWS) and wet season (WS) in Ro Vieng and Kandaul villages, Takeo province. In the treatment sites, F1, F2 and F3 represent fields that were 5, 50 and 100 m from the TBS, respectively. In the non-treatment sites, no TBS was applied.

3.3. Impact on rice yield

Across both seasons, the mean rice yield was significantly lower (17 to 37%) in the non-treatment sites than in the treatment sites in both Ro Vieng and Kandaul villages ($F_{1,36}$ = 72.8, P < 0.001; $F_{1,36}$ = 69.6, P < 0.001, respectively). In both villages, the mean yield was lower in the WS than in the previous season ($F_{1,36}$ = 19.4, P < 0.001; $F_{1,36}$ = 112.9, P < 0.001, respectively). However, in Ro Vieng, the difference in yield between seasons was more pronounced in the treatment sites ($F_{1,36}$ = 66.6, P = 0.014). In both villages, the distance to the TBS had no effect on yield (P > 0.05).

There was a negative linear relationship between cumulative rodent damage and yield ($P < 0.05$; Fig. 4). This relationship was strongest during the EWS and DS for Ro Vieng ($n = 18$, $R^2 = 0.93$, $p < 0.001$) and Kandaul ($n = 18$, $R^2 = 0.84$, $p < 0.001$), respectively. During these seasons, the slope of the regression indicates that for every 1% increase in rodent damage in Ro Vieng and Kandaul, there was a 74 and 42 kg ha^{-1} decrease in rice yield, respectively. Based on the rice yield value taken at the intercept, this is equivalent to a 1.3% and 0.76% decrease in rice yield, respectively, for every 1% increase in rodent damage.

In the WS, the regression was more scattered with a poorer fit (Ro Vieng: $n = 18$, $R^2 = 0.51$, $p = 0.001$; Kandaul: $n = 18$, $R^2 = 0.25$, $p = 0.033$). During this season, the slope of the regression indicates that for every 1% increase in rodent damage in Ro Vieng and Kandaul, there was a 28 and 40 kg ha^{-1} decrease in rice yield, respectively. Based on the rice yield value taken at the intercept, this is equivalent to a 0.6% and 1.1% decrease in rice yield, respectively, for every 1% increase in rodent damage.

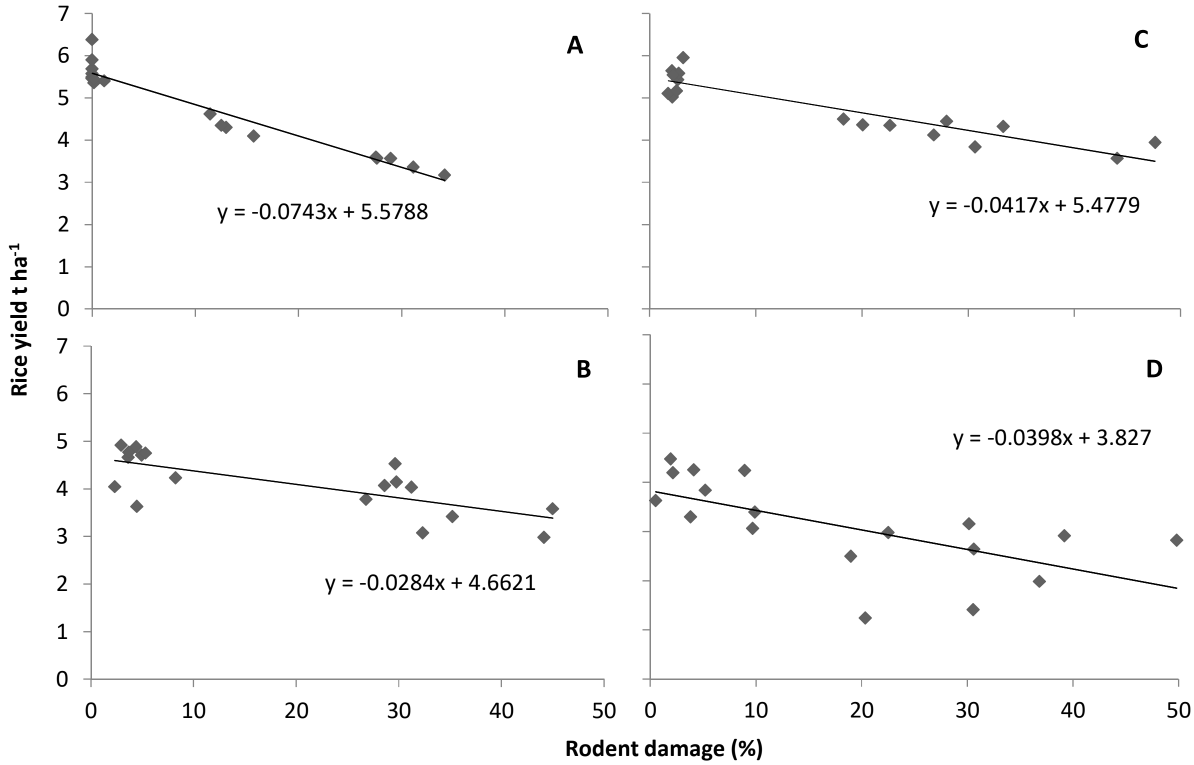

Fig 4. Correlation between cumulative rodent damage and rice yield in Ro Vieng village during the early wet season (A) and wet season (B), and in Kandaul village during the dry season (C) and wet season (D).

3.4. Economic analysis

In each 5 ha treated site, the total costs for EBRM activities ranged from 316 to 397 USD per season. Considering that this cost is shared between all farmers within the 5 ha site, this equates to a cost of 63 to 79 USD ha^{-1} per season (Table 1). This cost takes into account the non-paid out costs (or lost opportunity costs) for labour (i.e. two hours per day to check traps over the length of the cropping season at a wage rate of 0.125 USD hr^{-1}; Table 2). However, part of this cost was offset by selling rats caught to local sellers or to the market. We also were informed that some farmers opted to take trapped rats home for family consumption. The value of selling or harvesting rats was not included in our cost-benefit and net income calculations due to insufficient data (e.g. we did not differentiate between rats and mice, the latter of which has no market value due to their small size), but in Kandaul, we were informed that farmers were able to sell live rats at USD 0.75 USD Kg^{-1} and in Ro Vieng, farmers could get 2.50 USD kg^{-1}. Rats that had been killed by electric fencing fetch a much lower price of 0.25 USD kg^{-1} in Kandaul. If we assume an average weight of 150 g per rodent caught, we calculate that the value of the rats caught by the farmers in the Ro Vieng treatment sites was 19 to 28 USD ha^{-1} per season.

In the untreated sites, the total rodent management costs ranged from 1 to 424.99 USD ha^{-1} (Table 2). The highest costs were incurred during the DS in Kandaul due to the accumulation of hours required to check the electric fencing at night (6.5 hours per night over 70 days).

The mean rice production cost (including rodent management costs) for the non-treatment sites ranged from 455 to 639 USD ha^{-1} per season (Table 1). Based on the income calculated from crop cuts, the mean net income at these sites ranged from 193 to 320 USD ha^{-1} per season. Based on the difference in rice yield between the treatment and non-treatment sites, there was a 53 to 169% increase in net income following the implementation of EBRM and the benefit-cost ratios for EBRM ranged from 3:1 to 11:1 per season. The highest benefit-cost ratio occurred during the DS in Kandaul, largely due to the reduction in income spent on electric fencing.

Table 1. Mean rice grain yield for treatment and non-treatment sites, the calculation of the benefit-cost ratio and increase in net income following implementation of ecologically-based rodent management for the dry season (DS), early wet season (EWS) and wet season (WS) in Takeo province, Cambodia.

		Grain yield ($t\ ha^{-1}$ + SE)		Yield increase	Price of	Value of yield increase	Rodent management cost ($USD\ ha^{-1}$)[a]		Benefit-cost	Non-treatment sites		Increase in net income	% increase in net	Additional income from selling rats
Village	Season	Non-treatment	Treatment	($t\ ha^{-1}$)	rice kg^{-1}	($USD\ ha^{-1}$)	Non-treatment	Treatment	ratio	Rice production cost (USD ha-^{1})[b]	Net income (USD-^{1})[b]	(USD^{-1})[b]	income	($USD\ ha^{-1}$)[c]
Ro Vieng	EWS	3.85 (0.29)	5.63 (0.19)	1.78	0.19	338.88	16.75	60.70	6	454.95	276.00	330.93	120	27.7
	WS	3.73 (0.30)	4.51 (0.26)	0.78	0.19	147.66	16.03	60.70	3	444.87	264.38	138.99	53	19.05
Kandaul	DS	4.16 (0.18)	5.44 (0.17)	1.28	0.20	255.72	461.81	63.20	11	639.31	192.74	326.33	169	4.67
	WS	2.40 (0.40)	3.82 (0.29)	1.42	0.30	424.99	1.00	79.30	5	399.88	319.79	406.69	127	2.46

[a]Based on paid-out and non-paid-out costs; [b]Based on paid-out costs only; [c]Captures from kill traps not included

Table 2. Mean costs of rodent management (USD ha-1) in treatment and non-treatment sites for the dry season (DS), early wet season (EWS) and wet season (WS) in Takeo province, Cambodia.

Village	Season		CTBS[a]	LTBS[ab]	Kill traps	Rat campaign	Rodenticide[c]	Electric fencing[a]	Total paid-out costs	Labour non-paid-out costs	Total costs (paid out and non-paid out costs for labour)
Ro Vieng	EWS	Non-treatment					16.75		16.8		16.8
		Treatment	8.8	10.1	3	2.8			24.7	36	60.7
	WS	Non-treatment					16.0		16.0		16.0
		Treatment	8.8	10.1	3	2.8			24.7	36	60.7
Kandaul	DS	Non-treatment					10	101.8	111.8	350	461.8
		Treatment		20.3	3	2.8	5.1		31.2	32	63.2
	WS	Non-treatment					1		1.0		1.0
		Treatment		10.1	3	2.8	3.4		19.3	60	79.3

[a]The value for durable items (i.e. plastic, bamboo poles, traps, battery, power inverter) were halved

[b]LTBS length in Kandaul = 240 m per site in the dry season and 120 m per site in the wet season

[c]Rodentcide use in Kandaul treatment sites = 3 kg ha^{-1} in the dry season, 2 kg ha^{-1} in the wet season

4. Discussion

4.1. Reducing rodent damage and rice yield loss

The level of rodent damage recorded in our untreated sites confirms that rodent damage to rice poses a significant threat to food security and smallholder farmer livelihoods in Cambodia (Castilla, in press; Jahn et al., 1999; King et al., 2003). The implementation of a CTBS along with LTBS in intensive rice monoculture and a LTBS with bromadiolone rodenticide in recession rice growing areas reduced rodent damage by at least 84% for all cropping seasons evaluated. The level of success for the CTBS approach is comparable to previous studies (Brown et al., 2006; Singleton et al., 2003; Singleton et al., 2005b; Singleton et al., 1998) and provides further evidence to support this approach in intensive rice growing areas of Southeast Asia. As shown in previous studies, distance from the CTBS also had no effect on damage and yield, indicating that the level of protection of the CTBS extended to at least 100 m in the EWS and 150 m in the WS, within the 10 ha radius of protection previously reported (Brown et al., 2006; Singleton et al., 2003). We would thus expect the level of protection to extend beyond our 5 ha treatment sites.

In recession rice growing areas, the LTBS was very effective at removing rodents, as observed in maize growing systems in China (Wang et al., 2017). The high rodent capture rates and reduction in rodent damage thus demonstrates the suitability of this method for this type of agroecosystem. Unlike in rice monoculture, where rodents travel in many directions between rice fields and refuge habitats, we suspect that rodents generally travel in one direction in the recession rice landscape from the recently harvested rice growing area towards the newly planted rice crops. When the rodents reach the LTBS, the most accessible route is via the holes into the traps. The shorter length of the fence in the WS may explain why there was a slight increase in rodent damage 75 – 150 m from the fence during this season, and thus indicates some decrease in efficacy the further from the fence. A longer barrier, especially, a continuous barrier erected along the high water mark of the lake margin, is expected to provide a greater area of protection. However, this would require the coordination of more farmers and resources. Further research is needed to identify the suitability of this method in other landscapes where rodents migrate from one area to another.

For EBRM to be most effective, an integrated pest management approach should be applied (Singleton et al., 1999b). However, because of this, it is difficult to ascertain the individual value of each method. By comparing the number of rodents caught by each method, the LTBS was less effective than the CTBS in the rice monoculture, with similar numbers of rodents caught with kill-trapping. Based on research in maize cropping systems in China, Wang et al. (2017) hypothesize that thigmotaxis (the characteristic behavior of rodents to move along a physical barrier) is a more important factor in the success of the TBS rather than the attraction of trap crops. However, when comparing the trap success of the LTBS and CTBS in rice monoculture in this study, the CTBS clearly outperformed the LTBS. This suggests that in rice monoculture where *R. argentiventer* is the dominant rodent species, the attraction of the trap crop to rodents is a more important factor. Further research is needed to understand this mechanism for different cropping systems and rodent species, although, thigmotaxis is certainly likely to play a role in the success of both the CTBS and LTBS.

In this study, the rodenticide bromadiolone was applied in Kandaul village as an alternative to zinc phosphide and as a supplementary method of rodent control for the LTBS. However, in many Cambodian rice growing communities, rat hunting is regularly practiced and rodent meat is an important source of protein and income. It is thus inadvisable to apply rodenticides in such areas. As a minimum, rat hunting for consumption should be prohibited for two weeks following the end of the application of rodenticides, especially for anticoagulant rodenticides. However, if farmers cannot prevent free-ranging hunters from hunting in their land during this time, rodenticides should not be used. In recession rice growing areas, further research is needed to identify the optimum length of LTBS when no rodenticide is applied.

4.2. Relationship between rodent damage and yield loss

In the non-treatment sites, mean cumulative rodent damage ranged from 22-34% with a similar reduction in rice yield as compared to the treatment sites, indicating a direct relationship between rice yield loss and cumulative rodent damage measured at maximum tillering, reproductive and ripening crop growth stages. This was supported by the regression analysis which indicated a 0.6 - 1.3% reduction in rice yield for every 1% increase in cumulative rodent damage. The strong relationship in the DS and EWS, suggests that rodent damage was a common factor for all fields with little variation in other yield limiting or yield reducing factors, whereas in the WS, the higher variability between rodent damage and yield indicates that variation in rice yield was also explained by other factors such as variety, fertilizer use and other crop pests and diseases.

Often, when rodent damage assessments are made, they are only conducted at the ripening stage (Singleton et al., 2005a). However, as reported in this study and in previous studies, rodent damage occurs throughout the rice cropping season and can even be higher in previous crop stages (Singleton et al., 2005a; Singleton et al., 2003). In the non-treatment sites of this study, 37% and 40% of mean cumulative rodent damage occurred during the reproductive and ripening stages, respectively. Thus ideally, both of these crop stages should be monitored for rodent damage to get accurate assessments of yield loss. If only the ripening stage can be assessed, the results from this study suggest that this value should be multiplied by a factor of 2.5 to estimate cumulative rodent damage or by 2.3 to obtain an estimate of percentage yield loss due to rodents. This is slightly lower than previous calculations from studies in Malaysia and Indonesia, that suggest that damage estimates at ripening should be multiplied between three and seven times to estimate percent yield loss (Buckle and Rowe, 1981; Singleton et al., 2005a; Singleton et al., 2003).

4.3. Economic benefits

Farmers who adopted EBRM accrued economic benefits from increased yields (reduced damage) and sharing the costs of EBRM management options across five hectares. In addition, farmers benefit from the value of rats trapped and sold to sellers. In the non-treatment sites, the net income for paid-out costs was less than USD 320 per ha per season due to the high rice yield losses from rodents and high production costs. This is roughly half the net income for paid-out costs recently calculated for rice farmers in Vietnam and the Philippines during the low yielding season (Bordey et al., 2016). Following the implementation of EBRM, the net income of the treatments sites was at least 50% greater than the non-treatment sites, with farmers receiving double the net income in three out of the four seasons evaluated.

In a previous analysis of CTBS in Cambodia, the lower rice yields (0.6 – 2 t ha^{-1}) and higher equipment costs (40 USD ha^{-1}) did not appear to justify investment in the barrier (Jahn et al., 1999). However, based on the mean rice yields in our treatment sites, we calculate that the threshold rodent damage level for each tested EBRM approach to be economically viable (i.e. when the benefits outweigh the costs) was 5.7% and 5.8% for the Ro Vieng EWS and Kandaul DS, respectively, and 7.1% and 6.9% for the Ro Vieng and Kandaul WS, respectively. In our calculations, we included the lost opportunity costs for labour to check the traps. However, if there is no loss of income for this activity, e.g. if farmers are visiting the farm for other activities anyway, then the economic threshold should be lower. We would also expect greater value from the CTBS if the expected 10 ha coverage is included in the calculations. Our calculations were based on a five ha halo of protection. Alternatively, if rice farmers perceive that the risk of rodent damage is lower than the economic threshold, low cost methods of EBRM are advised, such as community campaigns, trapping and hunting early in the rice cropping season (before the rodent breeding season), synchronous cropping, extended fallow periods and maintaining field hygiene during the rodent breeding season. The implementation of a CTBS without the LTBS also has been proven to be sufficient in rice monocultures in Southeast Asia (Brown et al., 2006;

Singleton et al., 2003; Singleton et al., 2005b; Singleton et al., 1998). This would thus reduce the TBS costs by half.

The benefits and costs for integrated pest management are often measured against use of pesticides (Pretty and Bharucha, 2015). In the case of the two sites in this study, EBRM was compared with high-risk, labour and cost intensive options such as electric fencing. This study shows that alternatives that are safer for humans and the environment have benefits that outweigh those from current practices. However, consideration should be given towards the effect of discarded plastic on the environment and sourcing biodegradable materials where possible.

4.4. Locally adapting the technologies

Local adaptation of EBRM entailed adjustments in timing of management actions, coordinating activities by farmers, and the tools used, such as length of plastic barriers or number of traps or use of rodenticides. These changes were refined as the farmers continued to experiment with the EBRM techniques, similar to processes documented by Palis et al. (2008). For example, in Kandaul, the LTBS was set up earlier in the second season (WS) following the farmers request. Subsequently, high numbers of rodents were caught during this early crop stage and rodent damage to seedlings was reduced. Furthermore, as technical learning progressed, farmers learnt to coordinate the social mechanisms such as building interest for involvement in community rat hunting, or checking the traps in a shared experimental site. They also evaluated the value of trapped rodents as they interacted with sellers. The complementary information increases the capacity of farmers to make adjustments to their practices in the face of complex conditions, particularly regarding pest management (World Bank, 2007; Byerlee, 1987). Knowledge co-production among varied stakeholders such as between farmers, rat sellers, and manufacturers of traps for example, can enable financial incentives that support the adoption of EBRM practices by smallholder rice farming communities in Cambodia (Flor et al., 2016; Leeuwis, 2004).

4.5. Conclusions

Our results show that rodent damage to rice in Cambodia and the associated yield loss can be significantly reduced following the implementation of cost-efficient EBRM approaches that are locally adapted to village-specific agro-ecological and social conditions. By working closely with farmers in a participatory adaptive research approach, we successfully demonstrated that different rodent management options are suitable for different conditions, even within the same geographic region. To enable widespread adoption, strong support (e.g. from government extension, NGOs, etc.) is needed to facilitate cross-learning between farmers, local adaptation and community approaches to rodent management.

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