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Integrated rodent management in outbreak-prone upland rice growing areas of Northern Laos

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A B S T R A C T

An integrated rodent management program was tested in outbreak-prone areas in three provinces of the Northern uplands of Laos (Luangprabang, Phongsaly, Houaphanh). In each province, it was replicated in six villages and associated upland rice fields; six neighboring villages served as negative controls. The program started end of 2010 and aimed at protecting the wet season rice harvest of 2011 against rodent damage. Rodent control techniques included sustained trapping, rodent-proofing of grain stores, rodent hunts and village sanitation campaigns, and biological rodent control using the protozoan parasite *Sarcocystis singaporensis*. The measures were embedded in a community approach, which was coordinated by provincial and district agricultural officers. Compared to the control villages, which showed on average 10.9% rat damage to ripening upland rice before harvest in 2011, and to the situation of the previous year (12.8%), rat damage was significantly reduced to an average of 4.3% in rice fields of the treatment villages. The incidence of rat-infested rice storage huts dropped significantly from an average of 86% in 2010 to 3.5% in 2011 in the treatment villages. Villagers from Houaphanh culled a total of 73,088 rodents over a period of about nine months, which included mainly black rats (*Rattus rattus*). Because the program phased out before harvest in 2011, potential losses due to rodents were predicted based on yield-damage relationships of the crop year 2010. The predicted average reduction of yield loss for 2011 was 55%, or 417.6 kg ha^{-1}, in the treatment villages when compared to the controls. The program implemented principles of ecologically-based rodent management (EBRM), the components of which are discussed. In conclusion, EBRM could be helpful in stemming as what was observed as high chronic rodent populations in the uplands of Laos. True outbreaks will require development of a suitable forecast system.

1. Introduction

The livelihood of villagers in the uplands of Northern Laos is highly dependent on shifting cultivation agriculture and rice is the single most important food in Laos (Schiller et al., 2001). While the yield potential of traditional rice varieties may range between 3 and 3.5 t ha^{-1} without addition of fertilizer (Boualaphanh et al., 2011), rain fed rice is often grown for one season on hills with steep slopes where yields can be extremely low, ranging between 0.4 and 0.9 t ha^{-1} (Roder, 2001). Factors contributing to this include erratic rainfall and increased cropping intensity (Saito et al., 2006), general soil fertility and weed problems related to slash-and-burn practices (Roder, 1997), and rodents. Farmers cited rodents as a major constraint for growing rice in the uplands (Roder, 2001; Schiller et al., 1999). Recent historical analyses have documented that the Northern uplands of Laos experienced episodic rodent outbreaks with devastating effects in the past, when the entire harvest could be lost to rodents (Douangboupha et al., 2010). There is now scientific agreement that this is a regional phenomenon involving also neighboring countries and there exist linkages between bamboo masting events, rodent outbreaks, and famine (Normile, 2010). However, also during non-outbreak periods rodent problems persist in form of chronic infestations in Northern Laos (Douangboupha et al., 2003). Various rodent species are involved in the outbreaks (Douangboupha et al., 2010), but black or house rats

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(*Rattus rattus* Linnaeus) have been identified as a major pest species (Brown and Khamphoukeo, 2007). Recent molecular characterizations based on mitochondrial DNA place black rats from Laos under lineage II of what has been termed the *Rattus rattus* -Complex (Aplin et al., 2011), while other authors address these populations in Laos as the Asian house rat, *Rattus tanezumi* Temminck (Pagès et al., 2013).

To strengthen a selection of Northern upland villages in rodent management and protect the wet season rice of 2011, an integrated rodent management program was implemented as part of a long term measure, the Northern Uplands Development Program (NUDP). NUDP set out to improve land management and agricultural productivity in some of the poorest provinces in Laos, namely Luangprabang, Houaphanh, and Phongsaly (NUDP, 2015). Rodent control deemed especially urgent, because outbreaks threatened food security in the program area right from the start in 2010 (World Food Programme, 2009). The program integrated strategies of ecologically-based rodent management, or EBRM (Singleton et al., 1999), including community-based practices (Brown and Khamphoukeo, 2010; Palis et al., 2007) with campaigns of biological rodent control (Jäkel et al., 2006). The design of the program was experimental, as negative control villages were included to determine the impact of the actions. It was expected that the results of this relatively large-scale approach could be helpful in addressing future rodent problems and improve food security in the Northern uplands.

2. Materials and methods

2.1. Selection of target villages

The rodent management program was repeated in three provinces of the Northern uplands of Laos, namely Phongsaly, Luangprabang, and Houaphanh (PS, LP, HP), in three districts each. To identify suitable villages, a rapid community appraisal (RCA) was conducted in 231 villages, comprising about 14,000 households (HHs), all characterized by a high poverty status. In each village eight male and eight female farmers of different levels of income were interviewed with regard to rodent management. Parameters assessed included crop cultivation area, rice yield, damage and losses due to rodents, frequency of observations of rodents, villagers' motivation and rodent control practices. Thirty-six villages, 12 from each province, were finally selected based on comparable conditions regarding abundance of rodents (high frequency of observations), damage to rice (high losses), and willingness among farmers to engage in rodent control activities (medium to high motivation). Four each of the selected villages were located in the same village cluster of a district and considered a unit, two being randomly allocated as treatments and two as controls. This resulted in 18 villages (927 HHs; 709 ha upland rice) being assigned to the treatment group and 18 villages (1124 HHs; 1024 ha upland rice) serving as negative controls (Fig. 2). The negative control villages were about 11 km (median) away from each randomly assigned treated counterpart in the same district showing similar agricultural and natural habitats.

2.2. Design of the rodent management program and monitoring of implementation

The program was implemented over a period of about one year (start in October 2010), and included monitoring of parameters of rodent infestation and progress in community-based rodent management (Fig. 1). Conceptually, it followed a two-track approach: first, implementation of community-based rodent management in the villages and associated rice fields through a combination of sustained trapping (i.e., repeated application of snap traps over extended periods in different habitats and seasons), rodent proofing of the poles of rice storage huts (using metal guards), and rodent hunting and village sanitation with participation of the whole village; second, protection of upland rice fields by campaigns of biological rodent control using the parasitic protozoan *Sarcocystis singaporensis*, which is native to Southeast Asia (Jäkel et al., 1999).

Villagers of the treatment villages of HP volunteered in counting all rodents that were killed by snap traps, community hunts, and biological rodent control. In each village, a monitoring committee instructed fellow villagers and distributed forms for recording of culled rodents, which were re-collected on a monthly basis. Rodent carcasses were recorded under biological control, if they were not caught in a trap or killed by hunting, collected between nine and 15 days after application of rat bait, and showed typical signs of disease (bleeding or presence of dried blood around the nose and the eyes; Jäkel et al., 2006). Farmers revisited the places where they had applied rat bait to check for carcasses or moribund rats, which are usually apathic and can be sometimes observed in the open (Jäkel et al., 1999). Rodent species were identified following the taxonomic guidance of Aplin et al. (2003), and Lao names of rodents related to scientific nomenclature according to Aplin et al. (2006) and Bergmans (1995).

Nine agricultural officers (one from each district) of the Provincial and District Agriculture and Forestry Offices (PAFOs and DAFOs) supervised and monitored the rodent management activities of the villagers. They were trained in general rodent management and the specific methods applied in the program. In the negative control villages and associated rice fields no rodent control activities were conducted. Farmers followed their traditional practice. Treatment villages were provided for free with the necessary supplies of snap traps, metal guards, and rat bait on top of their already existing rodent control tools. Requirements for traps for each village were calculated based on the number of HHs and area of upland rice.

Locally contracted, independent interviewers interviewed farmers with regard to their common rodent management practices and application of the newly introduced techniques within a survey that was conducted separately from the monitoring activities of the program. The survey mainly focused on the economic situation of upland farmers while certain information points were assessed by differential phrasing of similar questions to check for the plausibility of the responses. In each district, 18 farmers were randomly selected for interview from residents lists of the treatment villages, which resulted in 54 interviewees province^{-1}.

2.3. Rodent proofing of rice storage huts

Metal guards were cut out of flat zinc sheets and usually 100 cm long. They were fitted to all poles of a rice storage hut in a way that protection extended to the higher part of the poles. A 30 cm–50 cm wide metal collar was added on top of each guard. Shorter poles were fitted with wider collars. Additionally, villagers removed parts of trees that were above or in contact with the storage huts, and lumber, animal feed, or livestock that was usually kept below. Holes in the walls were repaired. Rice was occasionally stored in metal wire cages, which was affordable for a minority of villagers only.

2.4. Biological rodent control

Commercial rat bait containing the parasitic protozoan *S. singaporensis* was provided by the local pest control operator General Service Lao (GSL) and applied as described previously (Jäkel et al., 2006). Two campaigns were conducted before, and one during the main rice growing season (Fig. 1). In each campaign, villagers

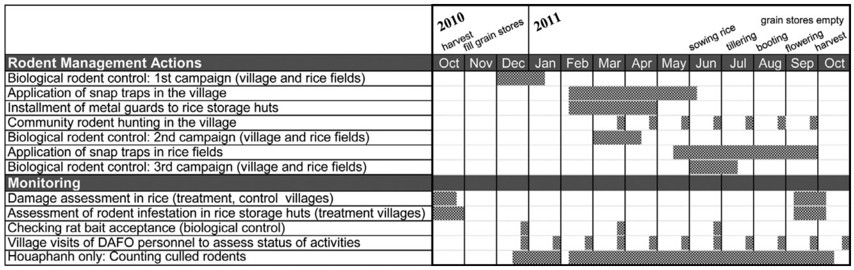

Fig. 1. Time schedule of the rodent management program.

distributed rat bait at about 250 pellets ha^{-1} in two or three rounds (interrupted by 14 day-intervals) with technical support of GSL on rice field bunds, forest borders, scrubland around villages, and other locations where rodents were expected to hide. Most of the area under rice was treated, but very remote fields were excluded due to time constraints. To protect stored rice inside the village, 30 rat bait pellets HH^{-1} were applied by villagers during one campaign.

Before application of biological control we assessed the risk of potential pathogenic effects on non-target rodents induced by high infection doses with *S. singaporensis* by comparing published (Jäkel et al., 1996; Häfner, 1987; Häfner and Frank, 1984) and unpublished results of infection experiments (using *Niviventer* sp. and *Maxomys surifer* from Thailand by one of the authors, T.J.) with the immunological (Watts and Baverstock, 1994) and molecular (Verneau et al., 1998) phylogenetics of Asian rodents.

2.5. Community-based rodent management

Work in the villages started by drawing 'resource maps' to identify locations where rodents appeared to hide and breed. Additionally, so called 'rodent champions' were identified, villagers that showed high interest in hunting rodents (Aplin et al., 2003) and helped convey rodent control techniques to fellow villagers. The snap traps distributed under the program were spring-loaded, with a metal base measuring 17.30 cm × 8.74 cm and a wire size of about 2.8 mm. This type of trap was commercially available in Laos, but not commonly seen in the Northern uplands where an all-wire spring trap imported from Vietnam was the dominant model due to frequent visits of Vietnamese traders in this area. The snap traps were used unbaited or baited with maize or rice. Villagers were advised to apply about 6 traps in or around the house, and about 30 traps ha^{-1} in rice fields. During a community hunt, rodent hide outs were tracked down in the field, along river banks and irrigation ditches, or under lumber in the village. Farmers then hunted at night using bamboo sticks, or during the day using dogs to track down rodents. Successful hunters were rewarded. Hunting also included installing nets around heaps of straw of rice or other crops while someone entered the target area and hit the heaps with a stick. Fleeing rodents were then caught in the net.

2.6. Assessment of rodent damage to rice and infestation of rice storage huts

Before the rice harvests in 2010 and 2011, provincial and district agricultural officers assessed rodent damage to maturing rice (% rat-cut tillers) in upland rice fields associated with the treatment and control villages (Fig. 1; no assessment was possible in the negative control villages in 2010). Sampling was conducted in upland rice fields that covered between 7% and 10% of the nominal area under rice of each village. Fields were selected randomly in a radius of about 1-h walking distance around the village. Two diagonal transects were laid through each rice field. On each transect, five equidistant points were marked with bamboo sticks. Then, a sampling frame (1 m * 1 m) was thrown randomly left or right along the marked points of each transect line and the total and rat-cut tillers was determined in each frame.

Rice storage huts of the treatment villages were checked twice for rodent infestations, before the intervention in 2010, and after rodent control in 2011 (Fig. 1). Monitoring was conducted by the rodent champions, who led a group of villagers to perform the task. The main criteria for presence of rodents in the rice storage huts were, in order of decreasing importance: a) direct sighting of rodents, b) presence of fresh rodent droppings, c) presence of typical spillage that rodents leave behind when gnawing on rice grains, and d) rodent tracks, which were visualized by placing small patches of sand in the corners of the huts. Huts were counted as infested, if one of the first three signs, or combinations thereof, were encountered. Tracks were counted in combination with one of the other signs of infestation only, because disturbance by other animals like lizards could hamper identification of rodent footprints.

2.7. Statistical analyses

The mean level of rodent damage to rice of treatment and control villages was analyzed by subjecting all measurements from the three provinces to a Two-Way ANOVA (of arcsine square root-transformed percentages) including the factors 'treatment' and 'district'. Pair wise comparisons employed the Holm-Sidak method at a 5% significance level. Pair wise comparison at district level assumed that due to geographical proximity the treatment and control villages were similar with regard to rodent problems. For comparing the medians of provincial incidence of rodent infested storage huts in the treatment villages a Kruskal–Wallis ANOVA on ranked data was performed including pair wise comparisons by Tukey Test at a 5% significance level. For analyzing the before-after scenario of rodent infestations of rice storage huts in consecutive years the Wilcoxon Signed Rank Test was employed. Yield-damage relationships of the crop year 2010 were analyzed by linear regression. Results of interviews were analyzed by constructing contingency tables and employing Chi-square statistics. The Yates correction for continuity was applied where appropriate. All tests were conducted using the statistical software SigmaPlot (version 11.0; Systat Software, Inc.).

3. Results

3.1. Rodent management practice of upland villagers before the intervention

There were no signs of ongoing rodent outbreaks in the study area at the onset of the program in 2010. However, as revealed by the RCA (231 villages) villagers reported rodents to be abundant and pose problems throughout the year. Among those who could recall the last serious outbreak, the median time span to that event was 360 days in HP (n = 9), 720 days in LP (n = 9), and 1080 days in PS (n = 10). Consequently, 66–68% of all HHs were actively engaged in rodent control, whereby villagers commonly used a locally available, all-wire spring trap imported from Vietnam. Interviews with 54 upland rice farmers from each province revealed that they usually applied 15.5 ± 3.2 (mean ± S.D.; LP), 16.4 ± 6.1 (PS), and 15.5 ± 3.0 (HP) snap traps in the rice field (on average 1 ha HH^{-1}), which was not significantly different between provinces (One Way ANOVA, d.f. = 15, $F = 0.631$, $P = 0.547$). However, 77% (PS) and 60% (HP) of the interviewees reported that they engaged in rodent control only during certain periods of the year (i.e., the cropping season), whereas 52% of the interviewees from LP reported to be active all year round. With regard to rodent proofing of rice storage huts eight out of the 12 selected villages of HP had their grain stores better protected (between 42% and 100% of all huts fitted with guards) than those in the other provinces, where storage huts of only three (PS) and one (LP) out of 12 villages showed fittings with metal guards. Villagers did not use metal guards consistently and often installed them improperly (e.g., too short, hut in contact with trees, lumber under the hut). Although individual farmers hunted rodents, community hunting was not common.

Despite of these efforts by upland farmers in controlling rodents, it appeared that the impact of their measures remained limited. This was indicated by the relatively high rat damage to rice in the control villages of PS and HP in 2011 (Fig. 2) and the high incidence of infested rice storage huts in most of the treatment villages before the intervention in 2010 (Fig. 3).

3.2. Impact of rodent management in villages and upland rice fields on pre-harvest rat damage in 2011

According to the monitoring records 70% or more of the HHs in each treatment village applied snap traps, had installed metal guards, and practiced community rodent hunts by end of March 2011. Biological rodent control was well received, because it appeared harmless to pet animals or livestock; there were no reports on non-target effects. Interviews with 54 farmers from each province in September 2011 revealed that 98% of the interviewees from HP used snap traps according to the recommended quantities. These proportions were significantly lower in LP (73.6%) and PS (72.0%) (Chi-square = 15.140; d.f. = 2; $P \leq 0.001$). The corresponding values for biological control were 98.1% in HP, 100% in LP, but only 66.0% in PS, which was significantly lower (Chi-square = 37.368; d.f. = 2; $P \leq 0.001$).

Rodent damage assessments in upland rice before harvest in 2011 revealed that all treatment villages showed lower mean damage values than the neighboring negative controls, whereby differences were statistically significant in eight out of nine districts (Fig. 2). Average rat damage of all treatment villages (4.3% ± 5.6%) was less than half when compared with the controls (10.9% ± 6.3%), and also markedly lower when compared with the situation before harvest in 2010 (12.8 ± 9.2%; ±S.D.; n = 18). The results of the Two-Way ANOVA including the factors 'treatment' and 'district' also revealed a statistically significant interaction between the two factors (Table 1). This indicated that the sizes of the effects of district (i.e., location) and treatment influenced each other. Pair wise comparisons (at $P \leq 0.05$) of the factor 'district' revealed that treatment villages of PS suffered significantly higher rat damage in six out of nine comparisons with districts of LP, and in seven out of nine comparisons with districts of HP. The rodent problems in the most seriously affected villages of May district in PS (Fig. 2) were due to high chronic rat infestations rather than an outbreak. Rodent control appeared to have been especially successful in HP, where rice fields of four out of the six villages were almost free of damage. In contrast, average rat damage to rice of the control villages in HP (14.0%) was similar to the situation in PS (14.1%), whereby only three out of nine district comparisons revealed significantly higher rat damage in PS. District comparisons between PS and LP showed that in five out of nine comparisons the control villages of PS had significantly higher rat damage than those of LP.

In support of the results in the treatment villages (Fig. 2) we additionally checked whether or not there was a relationship

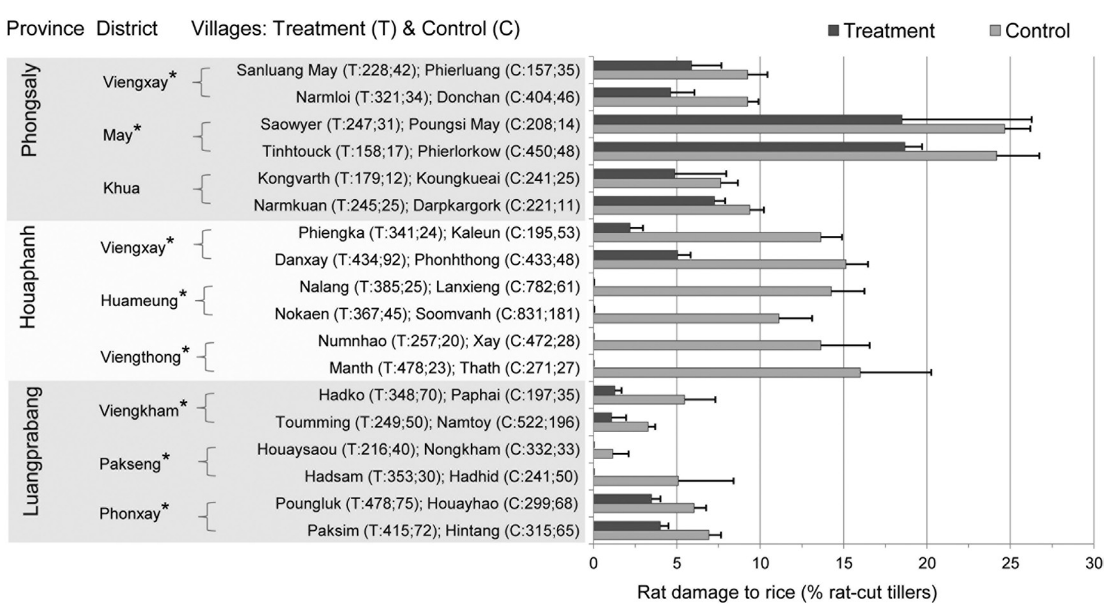

Fig. 2. Mean (±S.D.) damage by rats (% rat-cut tillers) to ripening upland rice of the treatment and control villages about two weeks before harvest in 2011. For each village between three and five upland rice fields were sampled. Asterisks indicate districts where a statistically significant difference between the treatment and the control villages was detected ($P \leq 0.05$), as determined by Two-Way ANOVA of the factors 'treatment' and 'district' using the Holm-Sidak method for post hoc pair wise comparisons. Numbers in parenthesis indicate the total number of villagers and the nominal area under rice (ha) of each village, respectively.

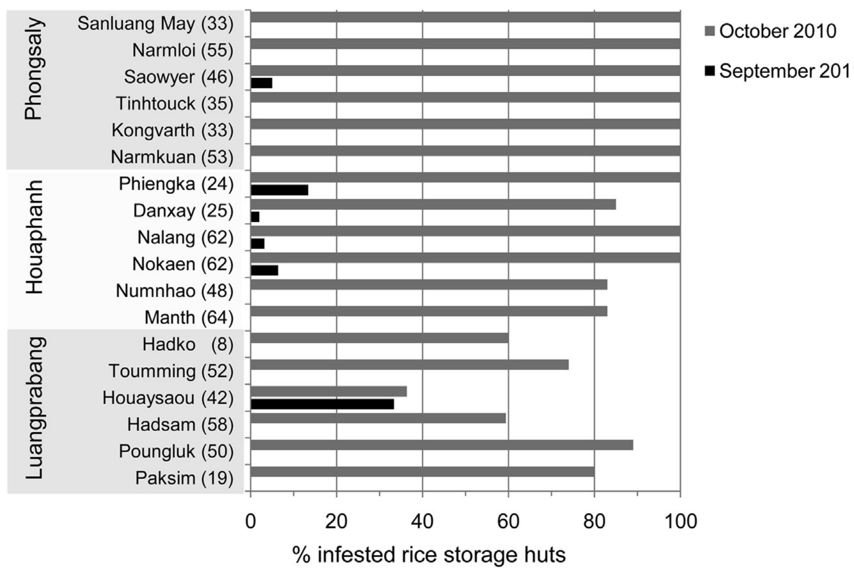

Fig. 3. Incidence of rodent infestation (% infested rice storage huts village^{-1}) in the treatment villages of the three provinces before (October 2010) and after (September 2011) the rodent management action. Numbers in parenthesis indicate the total number of rice storage huts in each village.

between the level of adoption of snap traps and biological rodent control by farmers (proportions of usage in %) as recorded by the interviews and the observed rat damage (%) at district level: when district values of both methods were combined and averaged there was a statistically significant negative correlation between usage and rat damage (Pearson Product Moment Correlation; n = 9, $R = -0.707$, $P = 0.0332$). For instance, higher rates of usage in districts of HP were related to lower rat damage, and the relationship was opposite regarding districts of PS.

The incidence of rodent infestation of rice storage huts averaged over all treatment villages was low (3.5%) by end of September 2011, whereby storage huts in 12 out of 18 villages were free of rodents (Fig. 3). This was significantly lower when compared to an average of 86.1% before rodent control at beginning of October in 2010 (Wilcoxon Signed Rank Test; n = 18, W = −171, T+ = 0, T− = −171, Z-Statistic = −3.733, $P \leq 0.001$). At that time the proportion of infested grain stores in PS was 100%, significantly higher than in LP (mean: 66.5%), but not different to HP (mean: 91.8%) (Kruskal–Wallis ANOVA; d.f. = 2; $H = 12.389$, $P = 0.002$). Due to time constraints it was not possible to record the situation in the control villages. According to observations on rodent droppings in grain stores, rats, not mice were damaging stored rice.

3.3. Results of rodent culls in Houphanh

A total of 73,088 rodents were killed in the six treatment villages of HP during the course of the rodent management program. This translates into an average of 12,181 rodents village^{-1} or 221 rodents HH^{-1} over a period of about nine months. Snap trapping contributed 32,368, biological control 20,874, and community hunts 19,846 rodents to the total catch. Subsamples from various locations indicated that about 80–100% of the dead rodents included black rats. Other rodent species encountered were the Ryukyu mouse (*Mus caroli*), the fawn-colored mouse (*M. cervicolor*), white-toothed rats (*Berylmys* spp.), the Himalayan rat (*Rattus nitidus*), the giant bandicoot rat (*Bandicota indica*), white-bellied rats (*Niviventer* sp.), the red spiny rat (*Maxomys surifer*), and the long-tailed giant rat (*Leopoldamys sabanus*). Rodents killed by biological control were almost all black rats; some specimens of *B. indica* were included, too. However, the number of rodents killed by this method is likely an underestimate, because a considerable amount of rodent carcasses probably remained undetected due to the extended time period between infection and death (Jäkel et al., 1999).

Table 1
Two-Way ANOVA of rat damage measurements in upland rice in 2011 (arcsine square root-transformed percentages; from Fig. 2) including the factors ‘treatment’ (treatment versus control villages) and ‘district’ of the provinces Luangprabang, Houaphanh, and Phongsaly (3 districts province^{-1}).

Source of variation	d.f.	SS	MS	*F*	*P*
District	8	0.383	0.0479	53.742	<0.001
Treatment	1	0.233	0.233	261.347	<0.001
District × treatment	8	0.127	0.0158	17.776	<0.001
Residual	18	0.0160	0.000891		
Total	35	0.759	0.0217		

d.f., degrees of freedom; SS, sum of squares; MS, mean squares; *F*, *F*-test statistic; *P*, probability.

3.4. Prediction of wet season rice yield losses of the crop year 2011

Because the program phased out before harvest in 2011, no information on rice yields could be obtained. Individual farmers from all provinces reported to be satisfied with the yield of the season, but information remained limited. Therefore, we tried to estimate potential losses due to rodents for the crop season 2011 based on pre-harvest rat damage measurements and yield data from 2010 (Fig. 4). Damage-yield relationships in lowland rice have shown that rates of yield loss due to rodents were similar across different cropping seasons (Singleton et al., 2005), suggesting their predictive potential for yield loss. The damage and yield averages of the samples were 17.01 ± 9.72% (±S.D., n = 29) and 1.41 ± 0.79 tons ha^{-1}, respectively. That year was characterized by poor and erratic rainfalls in Laos (FAO/WFP, 2011), probably providing a rather conservative yield estimate if compared with the wetter crop season of 2011 (FAO, 2011). Yield was similar to the 2009 (outbreak year) average of 62 villages (1.29 ± 0.89 tons ha^{-1}) that were recorded under the RCA to hold 80% or more upland rice. Employing linear regression analysis we determined that 1% additional damage was equal to 69.9 kg ha^{-1} yield loss (Fig. 4). The model was then used to predict the yield losses of the treatment and the control villages that corresponded to the rat damage measurements of 2011 (Fig. 2). With regard to the four villages in

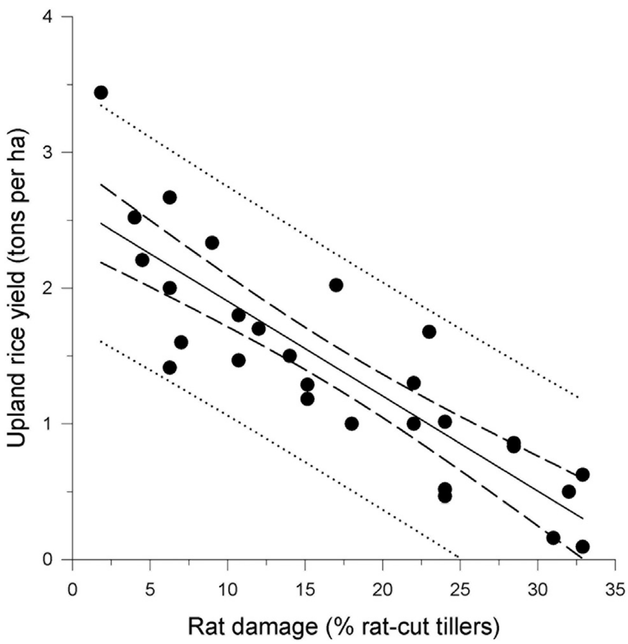

Fig. 4. Linear regression of yields of dried, unmilled upland rice on pre-harvest rat damage (% rat-cut tillers) measured in 2010 in ripening rice of 29 farm households, for which yields could be confirmed, in the provinces Luangprabang, Phongsaly, and Houaphanh. Confidence intervals for the mean (dashed) and for predictions (dotted) are included. Each damage value represents the mean of four random measurements. Linear regression: yield = 2.603–0.0699 * damage ($R^2 = 0.749$; d.f. = 28, $F = 80.719$, $P < 0.001$, power of test with $\alpha = 0.05$: 1.0). The slope = - 0.0699, i.e. 1% additional damage = 69.9 kg ha^{-1} yield loss.

PS, which showed the highest rat damage (18.5%–24.7%; Fig. 2), yield loss was predicted to range between 1293 and 1724 kg ha^{-1}, respectively. A uniform yield loss of 128 kg ha^{-1} was assumed for damage values ≤1.83%, because they were out of the predictive range of the equation. The estimated mean yield loss of the treatment villages (346.3 ± 76.3 kg ha^{-1}; ±S.D.) was significantly lower than the mean of the controls (763.9 ± 115.0 kg ha^{-1}) (T-test: $t = -12.842$; d.f. = 34; $P < 0.001$). This translated into an average reduction of losses as a result of rodent control by 417.6 kg ha^{-1}, or 55%, if compared with the controls (PS: 29%; HP: 83%; LP: 48%).

Because rats can inflict damage during various phases of the rice growing period, previous studies have determined the degree of cumulative damage in lowland rice. It was suggested to multiply rat damage only measured at ripening by 6.5 to obtain a cumulative damage estimate (Singleton et al., 2005). We tested this by incorporating various multipliers for rat damage into the regression model. Only a multiplier of 3 or lower produced potentially useful results, since estimated cumulative rat damage exceeded 100% at higher values.

4. Discussion

The successful reduction of rodent damage to upland rice and rodent infestations in storage huts in almost all treated upland villages indicates a significant impact of the rodent management practices that were implemented by the village communities. It shows that upland farmers in Laos can protect themselves against relatively high rodent populations, if they apply strategies of EBRM, such as implementing rodent control campaigns at key periods, improving general hygiene in the village, and working together as a community (Palis et al., 2010). The results of the rodent culls suggest that all rodent control methods contributed significantly to that success, and that infestation could actually reach a high level, at least in HP: if adjusted to a similar time frame of collection, numbers are roughly comparable to observations from a serious outbreak in the Ayeyarwaddy Delta region in Myanmar in 2009 (Singleton et al., 2010b). However, because this study included one wet season only and operations were implemented in areas without outbreaks, we suggest that the observed results should be only interpreted with regard to managing chronic rodent infestations. Previous studies have reported similar damage and losses due to rodents in the uplands of Laos (Brown and Khamphoukeo, 2010; Douangboupha et al., 2003), which suggests that the chronic rodent problem is a relatively constant factor if compared to the irregular outbreaks. Because outbreaks cannot be predicted in the moment (Douangboupha et al., 2010) and the time frame for the program was fixed, we increased replication by extending to different locations rather than to different seasons.

The design of the rodent management program was influenced by previous studies on the ecology of black rats in Northern Laos (Aplin et al., 2006), which had observed that rats migrated from rice fields to the villages after harvest and were breeding there. Furthermore, the usefulness of sustained trapping in controlling rats has already been well demonstrated (Brown and Khamphoukeo, 2010; Belmain et al., 2003). This knowledge was applied here in that the village communities started controlling rodents well before planting of the upland crop. We believe that preventive action not only helped reducing rodents inside the villages, but also contributed significantly to the reduction of rat damage in the rice fields. Considering that community hunts were mostly conducted in or close to villages and produced roughly a third of the total catch from HP, we estimate that about 50% of all culls occurred in or close to the villages. This supports previous reports suggesting the importance of villages as potential sources for re-invasion of rice fields (Douangboupha et al., 2009). It also underscores the need for proper post-harvest protection of grain stores, where black rats are the main pest species (Brown et al., 2009). Due to lack of the negative controls in the grain store protection program we cannot entirely attribute successful reduction of rodent infestation in the rice storage huts to rodent proofing, since environmental factors could have also influenced the outcome. However, we believe that a reduction of this magnitude is indicative of the effectiveness of rodent proofing. We further suggest that without the overall reduction of rodents in the village the outcome would not have been that clear-cut.

The extent of participation by villagers in the implementation of rodent management most likely influenced the different outcomes in the provinces. Although rodent damage to rice in 2011 was similar in HP and PS as indicated by the controls, villagers of HP were apparently more successful in controlling rodents. We attribute this to a higher degree of motivation (rate of participation) among villagers in HP province, as revealed by the interviews. This interpretation is also supported by the negative correlation between proportions of farmers applying rodent control (snap traps and biological control) and rat damage at district level. The reason behind this is not entirely clear, but it appeared that many villagers of HP were still influenced by the impressions that the last serious outbreak had imbued on them. Furthermore, the treatment villages of PS and LP reduced rodents significantly, but the rate of reduction appeared to be better in LP. This was probably due to the circumstance that rodent populations in PS were higher right from the start. However, while trapping efforts appeared to be similar in both provinces, use of biological control was more common in LP, which could have contributed to the better result. Why the villages of LP had a generally lower level of rodent infestation than those of the two other provinces could possibly be attributed to differences in the locations, an explanation supported by the interaction between the factors 'treatment' and 'district' in the Two-Way ANOVA of rat damage. Additionally, farmers of LP may have just been more active in rodent control as indicated by the interviews.

Whether or not the relatively high degree of participation of villagers could translate into a significant degree of adoption of EBRM in the future will depend on various factors. A major change that was introduced here related to the common indifference of villagers to rodents in the village: rodents are not perceived as a problem, an observation that was already reported by a previous study conducted in Luangprabang (Promkerd et al., 2008). By focusing on regular rodent control and sanitation in the village, this situation changed substantially. We think that future (self-) motivation of villagers and adoption of rodent control will depend on their understanding that rodent control in the village is as important as in the rice field. Since the interviews indicated that many farmers conducted rodent control only during the rice cropping season, a similar realization would acknowledge that this is necessary throughout the whole year. There is a high chance that snap traps, metal guards, and community hunts could be adopted on a larger scale, because they are already part of the common practice. Local snap traps and metal guards were largely affordable for upland farmers at the time of the study, and most of them wanted to buy the biological rodenticide, if it was locally available (Jäkel, 2011). It will be important to provide perspectives for the upland communities how to reduce costs for rodent control. For instance, although a gross increase in use of snap traps, as practiced here (i.e., numbers ha^{-1} were doubled), would result in higher costs this could be mitigated by sharing in the community and applications to more vulnerable rice crops based on factors such as crop stage, variety or location. The mechanisms that helped motivate farmers to implement EBRM included support by local government officials, visits of rodent experts, establishment of a village task force, and training of key farmers (Brown and Khamphoukeo, 2010; Flor and Singleton, 2010; Palis et al., 2010). In particular, the district agricultural officers were instrumental in motivating villagers to get involved in rodent management. In our view, wider adoption of EBRM in the Northern uplands will be feasible only, if the network of district agricultural officers with rodent expertise and sufficient funding for making visits to remote villages can be expanded to new districts and provinces.

Were the high levels of rat damage to rice in several villages of PS and HP signs of ongoing outbreaks, or just the consequence of high chronic rodent populations? There were serious outbreaks in the uplands in the wet seasons of 2008 and 2009 that led to unbearable conditions for rural families (World Food Programme, 2009). Houaphanh province was affected in both years, whereas PS experienced an outbreak in 2008 only (Douangboupha et al., 2010). This was confirmed by villagers during the RCA. However, during the present study the situation could not be characterized as an outbreak, a view that was also supported by villagers. Lao upland farmers generally draw a clear distinction between rodent damage suffered every year (chronic) and that suffered during outbreaks, which can be characterized as irregular but severe damage about every 10–15 years (Douangboupha et al., 2010). Although the cause of the outbreaks is not clearly understood, it is plausible that they are closely linked with the time of bamboo flowering and masting, similar to the situation in other countries where these outbreaks occur (Singleton et al., 2010a). Because it is the impression of farmers and agricultural staff in the upland provinces that high rat populations are now more frequent (Douangboupha et al., 2010), we interpret this as a sign of increasing chronic infestation levels. This could exacerbate the situation once a 'real' outbreak occurs. Our observations on mean rat damage to rice under traditional rodent control practice are quite in line with an average yield loss estimate of 12% for the uplands in Laos during a non-outbreak period (Brown and Khamphoukeo, 2010). On the other hand, they are also similar to rat damage measurements during an outbreak period in the Chittagong Hill Tracts in Bangladesh (Ahaduzzaman and Sarker, 2010). It could be possible that a combination of intensified cropping and reduced fallow periods in the uplands (Saito et al., 2006; Roder, 2001) is one reason why farmers observe high rat populations more frequently. Regardless of whether outbreak or high chronic rat infestation: the common practice of rodent control as observed before the intervention is not sufficient to stem the chronic rat tide, let alone a rat 'flood' during an outbreak.

According to our prediction of losses due to rats for 2011 the prospects for the rice harvest were significantly improved in the treatment villages. The loss estimates appear realistic, as they are based on yield data from 2010 that were similar to recordings from the outbreak year 2009 (3.4). Because we only measured rat damage shortly before harvest, there is no information on the cumulative damage and losses that rats usually can inflict over the whole rice growing period. Applying a multiplier of 6.5 to the damage data at ripening stage to estimate cumulative rodent damage as suggested for lowland rice (Singleton et al., 2005) did not return realistic values, probably due to a lower capacity of upland rice to compensate for that damage; this requires further research. The predicted average reduction of yield loss by 55% would more than compensate for an estimated average yield loss of 12% in upland rice due to rodents (Brown and Khamphoukeo, 2010). Given our estimates of potential yield loss for each village, the size of the villages and area under rice (Fig. 2), and an estimated annual rice consumption of 199 kg $person^{-1}$ in the uplands of Laos (Ramasawamy and Armstrong, 2012), one can estimate how a reduction of losses due to rodents would impact on the villagers' food security situation. For instance, if applied to the village pair Nalang (treatment) and Lanxieng (control) in HP, where treatment was quite successful, predicted total losses due to rats were equivalent to food required for 16 villagers (4% of the total villagers) as opposed to 305 villagers (39%) for one entire year, respectively. In the district May of PS with the highest rodent damage, predicted losses were high for both, the treatment (e.g., Tinhtouck: 111 villagers, or 71%) and the control villages (e.g., Phierlowkow: 407 villagers, or 91%). However, because we do not know the actual yield of every village and the size of the rice growing area that contributed to it, it was impossible to determine whether or not rice sufficiency was achieved through the intervention. According to single accounts of farmers it was, particularly in HP. Given that this province suffered a serious outbreak in 2009 (Douangboupha et al., 2010), and the relatively populous village Danxay, for instance, recorded an average rice yield of only 40 kg ha^{-1} (which translates into 3.7 tons of rice for 434 people) due to losses to rodents (unpublished results of the RCA), one can imagine the hardships the village went through.

When considering how to introduce biological rodent control to the upland villagers we thought it was advantageous to involve a professional pest control operator, because the delayed mode of action of the protozoan parasite *S. singaporensis* (Jäkel et al., 1996) required familiarization with a technology that was new to them. Safety was the main property that made villagers eventually accept biological control. The results of the culls suggest that the application was target-specific, although we cannot exclude the possibility that non-target rodents were affected since a significant number of rats may have died unaccounted for. Before application, we had assessed the risk of potential pathogenic effects caused by high inoculation doses of parasites on non-target rodents. The distinction between artificially 'high' (for rodent control) and naturally occurring, 'low' concentrations of infective stages is important here, because *S. singaporensis* is one of the most prevalent protozoan parasites in rodents in Southeast Asia (Jäkel et al., 2001a). Therefore, it is likely that many rodent species are exposed to the parasite in their natural habitats and have adapted to its presence. Furthermore, infection experiments have shown that artificially high doses of infective stages were only pathogenic for rats of the genera *Rattus*, *Bandicota*, and *Nesokia*, whereas in the case of other rodents that became infected no pathology occurred (Jäkel et al., 2001b, 1996; Häfner, 1987). These results closely matched with those of phylogenetic studies on Asian rodents based on molecular (Verneau et al., 1998: *Rattus* 'sensu stricto' group) and immunological parameters, the latter of which identified three main groups (Watts and Baverstock, 1994). Namely, phylogenetic group 3 contained all rodent genera immunologically close to *Rattus* and *Bandicota*, including *Berylmys*, *Bunomys* and *Paruromys*. The latter two have been found naturally infected with *S. singaporensis*-like stages (O'Donoghue et al., 1987). Hence, it could be expected that *Berylmys* spp., which occur in northern Laos (Douangboupha et al., 2010), were susceptible to infection but would not necessarily develop disease. Other rodents occurring in Laos (Duckworth et al., 1999) like *Leopoldamys* spp. or *Niviventer* spp. (phylogenetic group 2) and *Maxomys* spp. (group 1) were immunologically more distant to group 3 (Watts and Baverstock, 1994), hence, less likely to get harmed by the parasite. This was confirmed by unsuccessful attempts in the laboratory to induce infection or pathology in *Maxomys surifer* (Häfner, 1987; Häfner and Frank, 1984; Jäkel, unpublished observations) and *Niviventer* sp. from Thailand (Jäkel, unpublished observations) using high infection doses. Finally, rodent species that could have been negatively affected include the forest dwelling *Rattus sikkimensis* (syn. with *Rattus andamanensis*; e.g., Pagès et al., 2013) which is not known to occur in agricultural or village habitats in the uplands of Laos (Aplin et al., 2003), and other *Rattus* species which could be confused with black rats.

In conclusion, we think that EBRM that integrates sustained trapping and other locally available technologies with a strong community approach is a feasible approach for protecting villages in the uplands of Laos. However, because the rodent problem is large-scale in nature, it also calls for area-wide coordination mechanisms. This results in two levels of responsibility, at community and higher level, recommendations that were formulated in view of rodent outbreaks in Bangladesh (Belmain et al., 2010). Tactical application of biological rodent control, possibly coordinated on a larger scale through governmental support could help protect high yielding rice areas. Finally, research is needed to better understand the link between bamboo flowering and rodent outbreaks in Northern Laos and back up management of chronic rodent populations with a forecast system that could predict the next rat 'flood'.

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