Combining multi-scale socio-ecological approaches to understand the susceptibility of subsistence farmers to elephant crop raiding on the edge of a protected area

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Summary

1. Coexistence between subsistence farmers and elephants leads to problems for conservation and food security, especially on the edge of protected areas. Crop-raiding patterns have been investigated for decades, but understanding both social and ecological determinants remains a key challenge to defining realistic management options in a context of increasing human and elephant densities.

2. Hwange National Park, Zimbabwe, and its periphery, hosts one of the highest densities of free-ranging elephants. As scale is a critical element of ecological systems, we analysed the determinants of crop raiding at three spatial scales: the study area (217 households in 200 km²), the village (30 fields in 14 km²) and the edge of the refuge area (30 fields in less than 3 km²). We combined foraging ecology with sociological approaches, including a participatory experiment, to understand the processes behind the susceptibility of subsistence farmers to crop raiding.

3. Distance to refuge area was the most influential determinant in decreasing crop-raiding risk, with no damage occurring further than 4·4 km. We obtained consistent models between the three scales with high explanatory power for field damage at village and edge scales (94% and 68% respectively). Household density acted as an obstacle to elephants. Millet patches seemed to provide refuges, and thus promoted damage.

4. The participatory experiment allowed rigorous testing of the efficiency of traditional guarding practices. The presence of people was crucial for guarding efficiency. More innovatively, we demonstrated the role of neighbours and the importance of cohesive guarding as a promising strategy of reducing crop loss at the edge, primarily in areas with a high density of elephant paths.

5. *Synthesis and applications.* This paper provides evidence that multi-scale multidisciplinary approaches can unravel endogenous processes shaping human–elephant coexistence on the edge of protected areas. We believe that manipulating perceived risks for elephants, through mitigation methods based on the 'ecology of fear', and spatial organization of households, could create a 'soft fence' which, when combined with adequate incentives to farmers, promotes a better integration of the protected area in its territory.

Key-words: agricultural practices, ecology of fear, endogenous processes, Human–Wildlife Conflict, Hwange National Park, integrated conservation, land-use planning, participatory experiment, soft fence, traditional guarding methods

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Introduction

The trade-offs associated with human–wildlife coexistence, often referred to as human–wildlife 'conflicts', can result in direct negative human–wildlife interactions as well as human–human antagonisms about wildlife management options (Dickman 2010; Peterson *et al.* 2010). Many interventions have been proposed to reconcile human activities and wildlife needs, ranging from mitigations measures, incentives to increase tolerance and, when the costs are unbearable, to compensation schemes or even lethal control of 'problem animals' (Sillero-Zubiri, Sukumar & Treves 2007; Dickman, Macdonald & Macdonald 2011). Evidence-based conservation is fundamental for the management of practical conservation problems (Sutherland *et al.* 2004), and so is the understanding of the societal context (Dickman 2010). As the 'conflict' between humans and wildlife often depends on specific societal and ecological features of a given socio-ecological system, effective solutions are likely to be context dependent. However, understanding the role of endogenous processes in human–wildlife coexistence remains a general scientific challenge for integrated wildlife management.

The elephant is a flagship species and an emblematic animal when it comes to human–wildlife conflict both in Asia and Africa. As 70% of the range of African elephant *Loxodonta africana* (Blanc *et al.* 2007) and Asian elephant *Elephas maximus* (Choudhury 1999) occur outside protected areas, interactions with people are inevitable. These interactions are magnified by habitat fragmentation (Chartier, Zimmermann & Ladle 2011) and shifts from traditional agro-pastoral lifestyles to intensive agriculture (Fernando *et al.* 2005). In general, problem elephants damage crops, food stores and property, tamper with water resources and sometimes threaten human life (Sukumar 1990; Hoare 1999). Options for mitigating human–elephant conflict (referred to as HEC hereafter) range from traditional passive methods (e.g. using fire or planting chillies) to lethal control and land-use planning (Osborn & Parker 2003). For farmers living with elephants, investments in guarding induce significant additional indirect and opportunity costs (Naughton, Rose & Treves 1999; Osborn & Parker 2003). However, empowering local communities to take action and reduce the impact of HEC is thought to improve human perceptions of elephants and is considered as one of the most effective strategy to alleviate HEC (Naughton, Rose & Treves 1999; Davies *et al.* 2011). In a context where the current paradigm for sustainable megaherbivore conservation is the establishment of megaparks such as TransFrontier Conservation Areas (TFCA) (Jones 2006; Van Aarde & Jackson 2007), understanding the interactions between communal lands and protected areas is crucial to designing management options that will enable human–elephant coexistence (Van Aarde & Jackson 2007).

In Africa, one of the major costs of living with free-ranging elephants is the loss of cultivated food sources (Naughton, Rose & Treves 1999). Crop raiding by elephants exhibits temporal variations often related to the growing period of the crops (Sukumar 1994; Tchamba 1996; Osborn 2004), with seasonal peaks corresponding to the late wet season, often towards harvest (Tchamba 1996). Elephant forays into agricultural areas are generally less frequent than forays from other species, and highly clustered (Sitati *et al.* 2003), but the impact of a single elephant visit can be catastrophic (Tchamba 1996; Naughton-Treves 1998). Nutritional stress and mineral deficiency can play significant roles in increasing the propensity of elephants to extend their feeding habits to crop raiding (Chiyo & Cochrane 2005; Rode *et al.* 2006). Moreover, as the nutritional quality of crops is often much higher than wild plants (Sukumar 1990; Osborn 2004), they can represent food resources with considerable pay-offs (Sukumar 1994). Crop raiding is also influenced by mosaics of land uses, resulting from varying human densities and agricultural practices (Sitati *et al.* 2003; Fernando *et al.* 2005; Graham *et al.* 2009), and appears to be increased by forest refuges (Osborn 2004; Graham *et al.* 2010). Finally, as a 'high risk and high gain foraging strategy', crop raiding has been clearly shown to be advantageous for male elephants (Chiyo *et al.* 2011a) although crop raiding can involve family herds, individual males and bachelor groups.

Many authors emphasize that the analysis of spatially explicit data at relevant scales of the human–elephant interface should yield in-depth understanding of the conflict processes and hence more predictive models (Naughton-Treves 1998; Hoare 1999; Sitati *et al.* 2003; Osborn 2004; Graham *et al.* 2010). Accordingly, we combined ecological and sociological methodologies, in a spatially explicit multi-scale study, to focus on processes explaining crop-raiding intensity and farmers' susceptibility to crop raiding in a conflict hot spot on the edge of Hwange National Park (HNP). We hypothesized that crop-raiding patterns result from the trade-off between the benefits elephant can get from the available crops and the perceived risk induced by the human landscape (Naughton-Treves 1998; Sitati, Walpole & Leader-Williams 2005; Graham *et al.* 2010). More specifically, the larger-scale study aimed to describe the existence of a broad-scale pattern of crop raiding and assess whether every household was impacted by elephant at the periphery of HNP. We expected that households' farming practices (cultivated area and crop produced) could modify the predicted negative effect of the distance from the refuge area on the probability of elephant damage. At the village scale, we predicted that, in addition to distance, human settlements would reduce the level of crop damage in fields by increasing the perceived risks. Finally, at the edge of the refuge area, we designed a participatory experiment to explore how human guarding practices reduce the level of damage in fields. We expected that increasing elephant fluxes close to fields would decrease the effectiveness of guarding, and call for more cooperation between farmers.

Materials and methods

STUDY AREA

The study area is located in Hwange Rural District (Matabeleland North, Zimbabwe) and includes nine villages. This communal area is bordered to the south by the Main Camp area of Hwange National Park (HNP), to the east by Sikumi Forest (SF) and to the south-east by the town of Dete (long. 26°87′E, lat. 18° 62′S). The three scales considered in this study are the whole study area (200 km², Fig. 1), the village (Magoli, 14 km², Fig. 2) and the edge of a refuge area (a band of fields on the edge of SF, <3 km², Fig. 2).

The area, classified as agro-ecological region IV and V, is characterized by low fertility soils (mostly Kalahari sands) and erratic low annual rainfall (606 mm, inter-annual CV = 25%). The villagers rely essentially on subsistence farming and natural resource harvesting. Maize (*Zea mays*), sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*) are the main crops. HNP, a key protected area from the Kavango-Zambezi TFCA, hosts one the highest densities of free-ranging elephant in the world, particularly in the Main Camp area (mean = 4·36, SD = 2·67 elephants km⁻² in late dry season, Chamaillé-Jammes *et al.* 2009). The HNP elephant population, released from culling in 1986, has fluctuated around 35 000 individuals since 1992 (Chamaillé-Jammes *et al.* 2008). In our study area, most problems with elephants concern crop raiding; the few reported threats and injuries to humans involved wounded animals or bulls in musth. The number of crop raids is perceived as increasing in the past decade (C. Guerbois unpublished data).

DATA COLLECTION

Study area scale: semi-directive questionnaires at the household level

A preliminary survey conducted in April 2009 showed that problem elephants, witnessed at night only, came from adjacent protected areas (HNP and SF), mostly during the cropping season. Elephant crop raiding coincides with the growing period,

reaching a peak in March towards harvest time (C. Guerbois unpublished data). Between May and June 2011, we conducted semi-directive questionnaires at the household level in our nine studied villages (N = 217, Fig. 1). Households were selected following a stratified sampling design to cover all distances from the refuge areas. For each household, the GPS position was taken and distance (Dist) to the nearest protected area (either HNP or SF) was calculated using GIS software (Quantum QIS 1.6, Quantum Development Team 2010). Questionnaires were performed by local field assistants in the native languages of the respondents (Ndebele, Nambiya, Tonga or English). The area cultivated (CultA), the crops and average crop production (kg year⁻¹) were recorded for each household. We calculated an overall crop production index (CropProd) as the sum of all crop produced (in kg), and the relative proportions of the main crops (pMaize, pMillet and pSorghum). Problems involving wildlife for the past 3 years were also recorded. From 217 respondents, 72% claimed to have experienced problems, of which 32% included elephant. We built a binary response variable, with one representing at least one elephant problem occurring within the past 3 years.

Village scale: field data for damage assessment

After consulting with traditional authorities, in May 2009 just before harvest, we assessed elephant damage in 30 randomly selected fields in Magoli village, an HEC hot spot (Fig. 2). These fields were planted traditionally, and as seeds can germinate after several years, many different crop species can be found in a single field. To account for this heterogeneity and quantify the extent of elephant damage in each field, we applied a point quadrat sampling survey of crop damage by running parallel transects at 10-m intervals. Along each of these transects, every 5 m, all cultivated plants were recorded within a circle of 1 m radius. For each cultivated species, we recorded the state and number of all plants (intact/harvested/damaged) and animal sign (footprint/dung/type of damage). For damaged plants, we distinguished those eaten from those trampled. For each field, we calculated main crop species proportions (pMaize, pSorghum and pMillet) using the plant counts and built a binary variable to indicate the presence of other attractive food plants (AttPlant) such as sugar cane, watermelon and beans. We mapped all homesteads in our
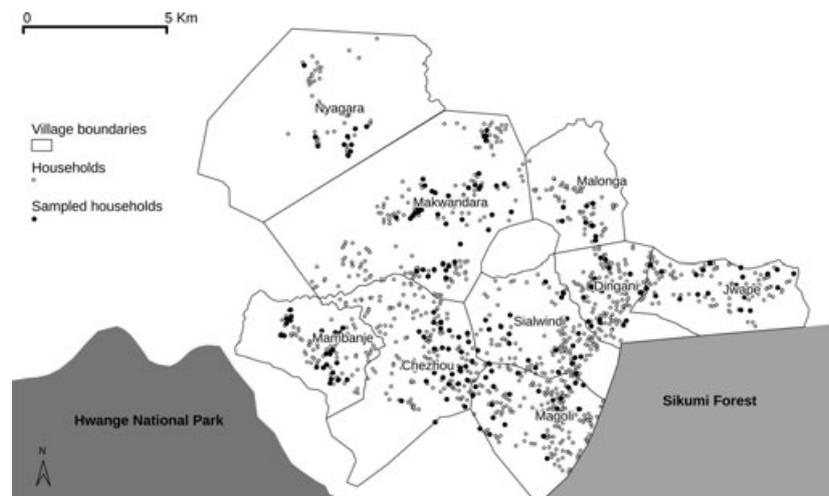
Fig. 1. Map of the study area: Hwange National Park and Sikumi Forest Area are daytime refuges for crop-raiding elephants. Households (including sampled households, *N* = 217) are represented for the nine studied villages.
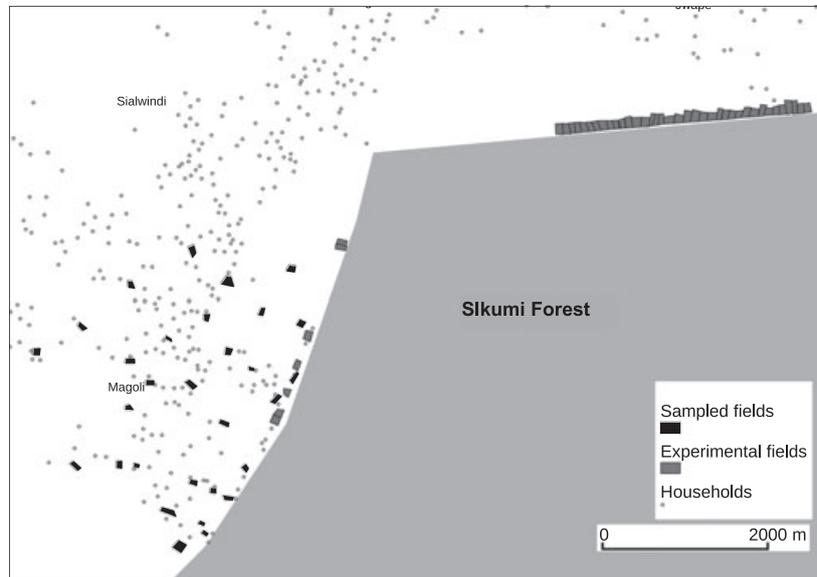
Fig. 2. Map illustrating the spatial distribution of households (white dots), the thirty sampled fields in Magoli (black polygons) and the thirty fields of the participatory experiment (grey polygons).

study area using Google Earth software (2011; version 6.0.2.2074, eye alt. = 2 km). A household influential area was considered to be 100 m around the centre of the yard and was materialized by a 100-m buffer on the GIS map (hereafter considered as 'household'). We also used our GIS to measure the shortest distance between the centre of the field and the edge of the closest refuge area (Dist), always SF in this case. To indicate the number of households encountered by an elephant while moving to a field from the refuge area, we drew the shortest line from the centre of each field to the edge of SF and counted the number of households intersected by this line (Hhenc). We recorded GPS positions of all elephant pathways (animals paths wider than 80 cm with significant elephant sign) crossing the boundary between SF and the communal fields. We built a binary variable (Elepath) taking one when pathways were absent in the 250-m section of edge closest to each field.

Edge scale: guarding practices in the participatory experiment

A participatory experiment was conducted from December 2009 to June 2010, involving 25 farmers, owners of a total of 30 two-acre fields right at the edge of SF, to eliminate any effect of distance from a refuge (Fig. 2). We selected fields as contiguous as possible and controlled for field attractiveness through homogeneous farming practices: same ploughing effort, same seeds variety and density (10 kg sorghum and 10 kg maize seeds per field). This allowed us to measure how the farmers' activities, field care and guarding efforts influence the level of elephant crop-raiding damage. We interviewed all the farmers through a semi-directive questionnaire to document the different methods used to deter problem elephants. During the farming season (November–June), we monitored bush clearing, weeding and fencing effort on a monthly basis to assess field care. At night, we drove transects along experimental fields on randomly selected dates and times (4–6 per month) to measure farmers' presence and effort, identify methods used and assess their efficiency in repelling elephants, at

least in the short term. Combining questionnaires and monitoring protocols, we built indices for farmers' guarding activities (Fact, based on methods used), farmers' guarding effort (Feffort, time spent in guarding activities) and farmers' field conditions (Ffield), scored according to the relative investment they represented (Table 1). For each field, we also built three indices for neighbours' activity (Nact), neighbours' effort (Neffort) and neighbours' field condition (Nfield), as the sums of the Fact, Feffort and Ffield indices from the two adjacent neighbours, when applicable. We calculated field production indices (Prodindex) using four 10 × 10 m quadrats per field (two in maize and two in sorghum) from which the harvest was weighed at the end of the cropping season. To account for the presence of elephant pathways, we built a continuous variable by counting the number of elephant paths on each side within 125 m from the middle of field edge along SF (Elepath). We conducted damage assessments every 2 weeks. As planting procedures were homogeneous, we

Table 1. Scoring used to estimate farmers' guarding indices (Fact, Feffort, Ffield). Scores reflect the relative investment required to implement the different traditional methods used for deterring elephants; for example, erecting a wire fence requires less materials, time and maintenance than building a guarding hut. Scores are cumulative; a farmer guarding on his own with a fire and a whip has an Fact = 5

Farmer's activity scores		Farmer's effort scores		Fields care scores	
Fire	1	Fire weekly	1	Fence (wire)	1
People (* nb of people)	1	Fire daily	2	Weeded	3
Drums	2	Presence weekly	1	Border cleared	3
Whips	3	Presence daily	2	Guarding hut	5
Scarecrow	3				
Burning chilli	4				
Burning tyre	4				
Torches	4				

assessed the level of damage directly, by estimating the proportion of the field destroyed. Analyses were performed on the cumulated level of damage until harvest.

STATISTICAL ANALYSES

Statistical procedure

Models describing patterns of elephant damage are presented for each of the three scales (study area, village and edge). Statistical analyses were conducted in three steps with some variations presented in the next paragraphs depending on our predictions and the models' structures. We first tested for correlations between quantitative explanatory variables and selected the variables relevant to our predictions. We then used the explanatory variables with significant effects in the baseline model to select the best models by using the normalized Akaike weight of each candidate model wi (Burnham & Anderson 2002). To facilitate the interpretation of our models, we presented standardized coefficients of the variables following Gelman & Hill (2007). Moran's *I*-tests were used to examine spatial autocorrelation (Bivand, Pebesma & Gomez-Rubio 2008). Detailed statistical procedures are presented in the Supporting Information (see Appendices S1, S2 and S3).

The adjusted R^2 of the regression of predicted values on observed values is given as an indication of the explanatory power of our models. All analyses were performed with the R 2.13 software (R Development Core Team 2011).

Elephant crop-raiding occurrence at the study area scale

Our sampling design required a hierarchical mixed model including 'Village' as the main random effect. We scaled our inputs variables and followed Zuur *et al.* (2009) for model selection in mixed effect modelling. We first selected the best random effect structure and then used a backward procedure for the selection of the optimal fixed effects minimizing the variance of the random effect (see Appendix S1 for details).

Modelling damage at the village scale

As the majority of plants damaged were eaten (mean = 0·83, SD = 0·17), we presented the analyses on total damage only. We performed a Friedman test for multiple dependent comparisons to test for differences in proportions of different crop species eaten by elephants across the 30 fields that we combined with Tukey post hoc tests to assess pairwise differences. After selecting candidate variables, we performed logistic regressions with binomial errors for proportion data to explain the proportion of crops damaged by elephant in fields as a function of distance from the refuge area (Dist), number of households encountered from the refuge area (HhEnc), presence of elephant path (Elepath) and proportions of the main crops (pMillet and pMaize). Candidate models included all single effects of the explanatory variables as well as all second-order interactions involving HhEnc. The assumption here was that field composition, the presence of elephant path and the distance from refuge area can moderate the effect of human settlement on the proportion of damage, the main hypothesis tested in this study at village scale. The detailed statistical procedure is provided in Appendix S2.

Modelling the proportion of damage in fields at the edge of protected areas

Eight of our experimental fields were not included in our analyses (two were never planted, three were heavily damaged by livestock, two showed very low production owing to infertile soil and one was invaded by weeds). We thus conducted our analyses on the 22 remaining fields. After removing highly correlated and non-significant candidate variables, we performed logistic regressions with binomial errors for proportion data to explain the proportion of damage in fields as a function of farmers' field (Ffield), farmers' effort (Feffort), neighbours' activity (Nact), number of elephant paths (Elepath) and the production (Prodindex). We hypothesized that an increase in elephant fluxes nearby would modify the effects of farmers' practices in reducing damage. Thus, candidate models included all single effects of the remaining variables as well as second-order interactions involving Elepath. Details on model selection are provided in Appendix S3. Paired t-tests were performed to test for differences in proportions of maize and sorghum eaten by elephants across all 22 fields.

Results

ELEPHANT CROP RAIDING IN THE STUDY AREA

The households in the two furthest villages (Nyagara and Makwandara) did not experience any damage from elephants. We found spatial autocorrelations in the binary response variable (Moran's *I*-test, $I = 8·76$, $P < 0·0001$). Zuur et al. (2009) recommended procedure led us to select a model with a random effect of village on the intercept (see Appendix S1). In the best model, the optimal fixed structure included the distance (Dist) and the proportion of millet (pMillet) as the only significant variables. The probability of crop raiding reported at the household level decreases, as expected, with the distance to the PA (Dist = $-2·048$, SE = 0·418, $P < 0·0001$) and increases with the proportion of millet produced by the household (pMillet = 0·433, SE = 0·209, $P = 0·038$). The variance of the random effect in the best model accounted for only 13% of its variance when considered alone (see Table S2.1 in Appendix S1). No spatial autocorrelation was found in the residuals of the best model ($I = -0·106$, $P = 0·54$) suggesting that our explanatory variables accounted for the spatial autocorrelation in the response variable (see Fig. S1 for an illustration of the spatial autocorrelation in the occurrence of elephant damage in our study area). This result strengthens the idea that distance from source acts as a major determinant of elephant crop raiding.

PROPORTION OF DAMAGE IN FIELDS AT THE VILLAGE LEVEL

We found significant differences between the proportion of crops eaten by elephant across the 30 fields (Friedman $\chi^2 = 7·64$, d.f. = 2, $P = 0·022$), with millet being significantly less eaten than maize (Tukey post hoc test:

$P = 0.017$). The best model included Dist, HhEnc, pMaize, pMillet, Elepath and three interactions (Dist:HhEnc and HhEnc:pMillet and HhEnc:Elepath) with an explanatory power of 94% of the variance ($F_{1,28} = 482.2$, $P < 0.0001$). The Table 2 summarizes the linear contributions and the standardized estimates of the parameters retained in this complex best model (the raw coefficients are available in Table S1). We also illustrated the outputs of this model in a series of figures (Fig. 3). Overall, the single effect of distance, as expected, significantly reduced the proportion of damage and explained by itself 62% of the deviance of the best model. Although it was correlated to distance, the number of households was highly significant in reducing the proportion of damage. The standardized coefficients (Table 2) even suggest that the effect of the interaction HhEnc:Dist was greater than the effects of the variables alone, thus suggesting that they acted synergistically (Fig. 3a). The presence of elephant paths nearby and an increasing proportion of millet in fields increased the proportion of damage (Fig. 3b,c), mostly through their antagonistic effect on HhEnc, suggested by their significant interactions (Table 2). The proportion of maize contributed only slightly to the proportion of damage. Finally, even though there was spatial autocorrelation in the proportion of damage at the village scale ($I = 4.96$, $P < 0.0001$), there was no spatial autocorrelation left in the residuals of the best model ($I = -1.379$, $P = 0.92$, see Fig. S2). Overall, our results at village scale suggest that the observed spatial autocorrelations mostly resulted from the complex interplay between distance and anthropogenic landscape components (Fig. S2). As expected from our original hypothesis, the human settlement acted as a mitigation force for elephant damage to fields.

PROPORTION OF DAMAGE IN FIELDS AT THE EDGE OF HNP

There was no significant difference between the proportion of maize and sorghum eaten across our experimental fields (paired *t*-test, $t = -0.88$, d.f. = 18, $P = 0.389$). There was no spatial autocorrelation in the observed damages in the fields at the edge (Moran's *I*-test: $I = -0.0098$, $P = 0.504$). The best model included farmers' effort (Feffort), farmers' field care (Ffield), neighbours' activity (Nact), number of elephant paths (Elepath) and the interaction Nact:Elepath (see Appendix S3 for statistical procedures and model selection), with an explanatory power of 68% ($F_{1,20} = 45.22$, $P < 0.0001$).

The farmers' field care accounted for 34% of the deviance and significantly reduced the proportion of damage in fields at the hard edge (Table 3). Our results demonstrate that the level of damage was reduced by farmers' effort, and neighbours' activity (Fig. 4a). As expected, an increase in the number of elephant paths increased the level of damage, but amplified the effect of neighbours' investment in guarding (Table S2), with most noticeable effect for neighbours' investment below 10 (Fig. 4b). Furthermore, the standardized estimates (Table 2) suggest that the effect of neighbours' activity contributes as much as the farmer's investment in his field in decreasing the proportion of damage. These results support our hypothesis that social cohesion is likely to reduce the proportion of damage, particularly in presence of high elephant fluxes.

Discussion

ELEPHANT CROP RAIDING ON THE EDGE OF HNP

Combining sociological and ecological approaches at three scales gave complementary and consistent results, and allowed us to refine small-scale mechanisms behind the observed patterns of crop damage. The distance from refuge areas explained much of the variations in crop damage, and this is consistent with the hypothesis that the perceived risk increases with distance from a refuge area (Naughton-Treves 1998; Graham *et al.* 2009, 2010). No elephant damage occurred further than 4400 m from

Table 2. Linear contribution of the parameters modelling proportions of damage in fields at village scale (Best model = M1, see Appendix S2 for details in model selection)

Parameters	Resid. d.f.	Dev.	Resid. dev.	P	Standardized estimates
NULL	29		2166.56		
Dist	28	1332.85	833.71	<0.0001	−46.49
HhEnc	27	464.91	368.8	<0.0001	−46.64
pMillet	26	80.03	288.77	<0.0001	2.96
pMaize	25	7.98	280.79	0.0047	−0.57
Elepath	24	5.19	275.61	0.0228	5.57
Dist: HhEnc	23	122.27	153.34	<0.0001	−108.53
HhEnc:pMillet	22	19.81	133.53	<0.0001	6.29
HhEnc:Elepath	21	58.27	75.27	<0.0001	12.91
(Intercept)					−21.68
Adj. R^2 = 0.94					

Dist = distance from refuge area, pMillet, pMaize = proportion of millet and maize, HhEnc = number of households encountered from the refuge area, Elepath = presence of elephant paths. Standardized Estimates were calculated following Gelman & Hill (2007).
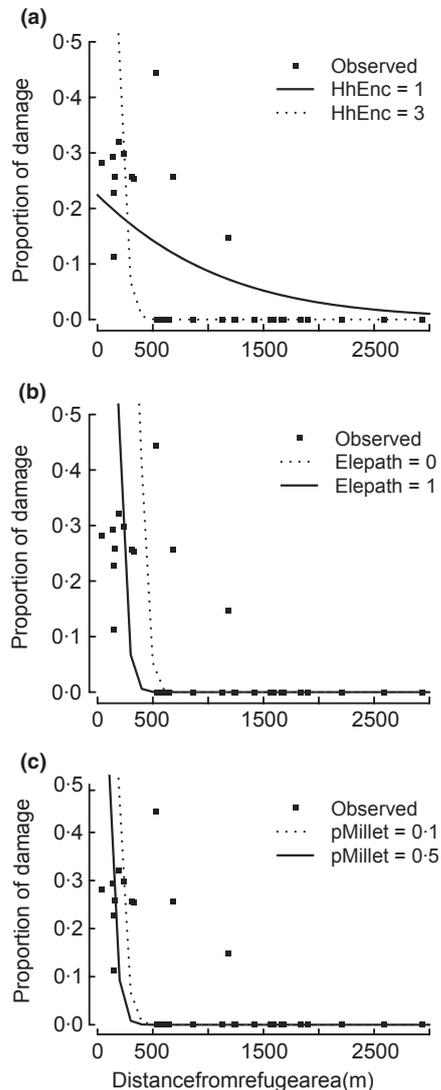
Fig. 3. Factors affecting the proportion of damage in Magoli fields. (a) Effect of an increasing number of households encountered (other parameters: pMillet = 0·6, Elepath = 0, pMaize = 0·12). (b) Effect of the presence of elephant pathways (HhEnc = 3, pMillet = 0·6, pMaize = 0·12). (c) Effect of a decreasing proportion of millet (HhEnc = 1, Elepath = 0, pMaize = 0·12).

Table 3. Linear contribution of the parameters modelling proportions of damage in fields at the edge (Best model = M15, see Appendix S3 for details in model selection)

Parameters	Resid. d.f.	Dev.	Resid. dev.	P	Standardized estimates
NULL	21		227·83		
Ffield	20	77·05	150·78	<0·0001	−1·10
Nact	19	17·98	132·81	<0·0001	−0·79
Feffort	18	5·81	127·00	0·0159	−0·52
Elepath	17	4·95	122·50	0·0261	−0·44
Nact: Elepath	16	24·12	97·93	<0·0001	−1·53
(Intercept)					−1·80

Adj. R^2 = 0·68

Ffield = farmer's field care, Nact = neighbours' activity, Feffort = farmer's effort and Elepath = number of elephant paths. Standardized Estimates were calculated following Gelman & Hill (2007).
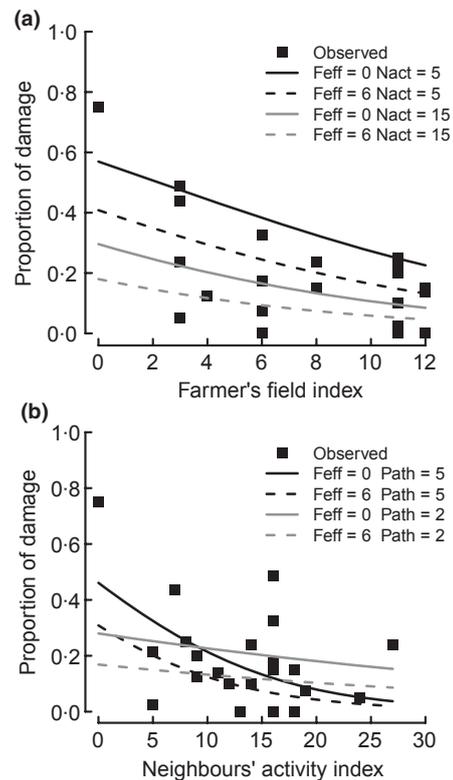
Fig. 4. Factors affecting level of damage observed at the edge of the refuge areas. (a) Effects of farmer's effort, neighbours' activity and field care (other parameters: Elepath = 5). (b) Interaction between farmer's effort, number of elephant pathways and neighbours' activity (Ffield = 8).

the edge. The proportion of millet damaged was positively correlated with the probability and level of elephant damage. As millet was not more eaten than maize or sorghum, we suggest that millet fields are used more as cover for refuge than as feeding sites. Millet can often be taller than 3 m, hence a greater proportion of millet within the landscape can induce a mosaic of potential refuges, thus reducing the perceived risk of detection. The size of the cultivated fields and the production index of the fields did not significantly influence crop raiding. The study area is characterized by fields with very low production (on average < 200 kg ha^{-1} of grain) and the heterogeneous mosaic of small-scale subsistence farming makes the quality of patches less predictable to elephants. Our results at the village scale show that the number of households

encountered when moving out of the refuge area significantly reduced the level of damage. The interaction between elephant paths and households encountered suggests that the deterrent effect of households may be attenuated by greater local fluxes of elephants. Despite the 'hiding' opportunities suggested by the effect of millet, it is difficult to determine whether this household effect is

linked to higher perceived detection risk or to active disturbance of elephants by people, or both.

Even though crop raiding was correlated in space at the study area and the village scales, these spatial autocorrelations resulted mainly from the interplay between the distance from refuge area and anthropogenic landscape features. Overall, our results support the hypothesis that crop-raiding patterns result from the trade-off between the benefit elephant can get from crops and the perceived risks associated with human-dominated landscapes (Sitati, Walpole & Leader-Williams 2005; Graham *et al.* 2009; see also Valeix *et al.* (2012) for an example of such a trade-off in large carnivores).

EFFICIENCY OF TRADITIONAL GUARDING PRACTICES AT THE EDGE OF HNP

In the participatory experiment, we controlled for spatial heterogeneity in the risk of crop raiding by fixing distance from refuge areas to zero and controlling crops planted. Measuring guarding efficiency required a combination of questionnaires and field monitoring data (such as night transect surveys). We chose to distinguish farmer's activity from farmer's effort and field care as we found it more appropriate to describe the inputs of our farmers' community adequately. However, farmer's activity and effort were correlated and so were neighbours' activity and effort (see Appendix S3). In our analyses, farmer's effort and neighbours' activities were retained as they were the least correlated, each giving an independent measure of the farmer's and the guarding efforts of neighbours. Using semi-quantitative indices is always liable to some subjectivity; however, in our case the same observers always assessed the farmers' involvement, so the values of the indices should be consistent. Having observed and lived with farmers during the whole cropping season, we believe that our qualitative assessment behind these semi-quantitative indices is meaningful (see Drury, Homewood & Randall 2011 for the debate on qualitative data in conservation ecology research) and reflects the complexity of decision-making by farmers in the face of uncertainty, restricted manpower and logistics. Davies *et al.* (2011) suggested that field experiments usually suffer from unbalanced design and non-independence when derived from 'natural experiments'. We think that our controlled participative design was robust to compare farmers' inputs in field care, guarding activities and efforts. People's presence was highly influential, and overall, our results confirm that increasing human effort can reduce the impact of crop raiding (Sitati, Walpole & Leader-Williams 2005). Furthermore, we showed that an increase in the neighbours' activity can significantly reduce the level of damage, particularly so for the farmers whose investment in guarding is low, and for fields close to major elephant pathways. This result is new, and to our knowledge, the importance of cohesive guarding has never been fully investigated. If cohesive guarding is planned, then it will benefit the whole community by allowing lower investment by individual farmers. As for the effect of millet at the village scale, the influence of field care (mostly clearing field borders and weeding) suggests that increasing visibility and early detection can significantly decrease the level of damage (Osborn & Parker 2003; Sitati & Walpole 2006).

LESSONS FROM COMBINING APPROACHES AND SCALES

The proportion of the variation explained by our models is very high compared with that provided in previous studies. This supports the idea that combining approaches at appropriate scales is crucial to a better understanding of processes underlying human–wildlife coexistence. We support Graham *et al.*'s (2010) suggestion that spatial analysis of HEC should assess the strength of predictor variables at different spatial extents to distinguish factors that are important at the regional level from factors that operate within the specific HEC areas vulnerable to crop raiding. Here, we focused on a HEC hot spot and developed local predictors, but as recommended by Du Toit (2010) we explicitly built our approach on multi-scale spatial comparisons to test for the robustness of our conclusions. We suggest that this kind of combined approach should be replicated in other systems with serious human–wildlife coexistence issues. The qualitative data collected during long-term socio-ecological protocols by researchers living within the system should be also seriously considered as a way to highlight endogenous processes shaping local coexistence between humans and wildlife in different socio-ecological systems.

Short-term mitigation can only reduce, and not eradicate, the problem (O'Connell-Rodwell *et al.* 2000); therefore, we believe that integrating the human and elephant components simultaneously is the way forward to understand the limits of long-term co-viability between rural communities and elephants, and identifying a portfolio of acceptable and realistic land uses and management options for mosaics of land uses. The challenge therefore is to integrate elephant dynamics, forage quality, human activity and landscape structure as well as human–elephant management strategies into a socio-ecological framework. This implies accounting for socio-ecological space and time scales, but also incorporating social representation and organization (Cumming, Cumming & Redman 2006).

IMPLICATIONS FOR FUTURE MANAGEMENT

Here, we described crop-raiding patterns in subsistence farming areas exposed to very high elephant densities. Elephant crop-raiding behaviour appeared to be opportunistic and affected by people's settlements and activities. We showed that damage was correlated with the presence

of elephant paths, as found by Sukumar (1994) in new settlements created along traditional elephant paths. This suggests that historical elephant routes should be accounted for when planning human settlement and designing elephant corridors. Furthermore, we think that manipulating human practices and settlements along protected areas can affect elephant behaviours by acting as a 'soft fence' between agricultural and protected areas. For instance, Graham *et al.* (2009) suggested that habitat selection by elephants is negatively influenced by the presence of livestock and herders. As previously shown, densely settled areas acted as barriers to elephant incursions into agricultural land (Naughton-Treves 1998). However, we believe this can work only if elephants associate human landscapes with perceived risk, meaning that at some stage elephants must be disturbed. Because habitual crop raiders can be replaced by other elephants, lethal control of elephant will have limited effects on HEC (Chiyo *et al.* 2011b), but could still contribute to the perception of high risk. As animals learn much of their behaviour during their lifetime, it may be possible to deceive them into learning to fear people by using methods based on 'psychological warfare' (Sukumar 1994). Overall, managing problem animals would benefit from integrating the 'ecology of fear' (Brown, Laundré & Gurung 1999), either directly (lethal control and disturbance gunshots) or indirectly (use of bees as in King, Douglas-Hamilton & Vollrath 2011).

From the sociological perspective, incentives for new land uses or implementing new practices, such as cohesive guarding, should be created. This could combine novel passive, cost-effective and income-generating methods (e.g. Osborn 2002 for chilli pepper; King, Douglas-Hamilton & Vollrath 2011 for honey) and direct 'in kind' payments (Ferraro & Kiss 2002), particularly in low-income communities. We also suggest that areas managed according to traditional rules and land-use practices should be part of an elephant conservation strategy, where people and elephants have to share resources (Fernando *et al.* 2005). Cumming, Cumming & Redman (2006) demonstrated how mismatches between the scales of ecological processes and the institutions that are responsible for managing them can contribute to a decrease in socio-ecological resilience. For instance, when sharing elephant meat from shot problem animals, people living at the edge often question the lack of recognition of their status by responsible authorities (C. Guerbois, pers obs.). This can typically result in human–human conflicts about wildlife. We believe these examples illustrate how endogenous rules of governance and resource uses could contribute to a better management of socio-ecological systems, including a protected area.

Acknowledgements

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Fig. S1. Spatial autocorrelation in crop-raiding occurrence (study area scale).

Fig. S2. Spatial autocorrelation in proportions of damage in fields (village scale).

Table S1. Best model retained to describe proportions of damage in fields (village scale).

Table S2. Best model retained to describe proportions of damage in fields (at the edge).

Appendix S1. Statistical procedures for describing crop-raiding occurrence (study area scale).

Appendix S2. Statistical procedures for modelling proportion of damage in fields (village scale).

Appendix S3. Statistical procedures for modelling proportion of damage in fields (at the edge).

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