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Predicting spatial aspects of human–elephant conflict

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Summary

1. Human–elephant conflict (HEC) in Africa occurs wherever these two species coincide, and poses serious challenges to wildlife managers, local communities and elephants alike. Mitigation requires a detailed understanding of underlying patterns and processes. Although temporal patterns of HEC are relatively predictable, spatial variation has shown few universal trends, making it difficult to predict where conflict will take place. While this may be due to unpredictability in male elephant foraging behaviour (the male behaviour hypothesis) it may also be due to variations in the data resolution of earlier studies.

2. This study tested the male behaviour and data resolution hypotheses using HEC data from a 1000-km^2 unprotected elephant range adjacent to the Masai Mara National Reserve in Kenya. HEC incidents were divided into crop raiding and human deaths or injuries. Crop raiding was further subdivided into incidents involving only male elephants or family groups. A relatively fine-resolution, systematic, grid-based method was used to assign the locations of conflict incidents, and spatial relations with underlying variables were explored using correlation analysis and logistic regression.

3. Crop raiding was clustered into distinct conflict zones. Both occurrence and intensity could be predicted on the basis of the area under cultivation and, for male elephant groups, proximity to major settlements. Conversely, incidents of elephant-induced human injury and death were less predictable but were correlated with proximity to roads.

4. A grid-based geographical information system (GIS) with a 25-km^2 resolution utilizing cost-effective data sources, combined with simple statistical tools, was capable of identifying spatial predictors of HEC. At finer resolutions spatial autocorrelation compromised the analyses.

5. *Synthesis and applications*. These results suggest that spatial correlates of HEC can be identified, regardless of the sex of the elephants involved. Moreover, the method described here is fully transferable to other sites for comparative analysis of HEC. Using these results to map vulnerability will enable the development and deployment of appropriate conflict mitigation strategies, such as guarding, early warning systems, barriers and deterrents. The utility of such methods and their strategic deployment should be assessed alongside alternative land-use and livelihood strategies that limit cultivation within the elephant range.

Key-words: African elephant, crop damage, GIS, human casualties, Kenya, spatial analysis

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Introduction

Many species face increasing competition with people for space and resources (Pimm *et al*. 1995; Balmford *et al*. 2001). As a result, some are coming into increasing conflict with people, and this is particularly true of large mammals. Large herbivores, such as the black rhinoceros *Diceros bicornis* L., and large carnivores bear most of the cost of this conflict and are either critically endangered or declining rapidly (Woodroffe & Ginsberg 1998; Emslie & Brooks 1999). Others, such as the African elephant *Loxodonta africana* Blumenbach, also have considerable impact on people and are in the unusual

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position of being simultaneously an endangered species (IUCN 2000) and, in places, a pest species.

Human–elephant conflict (HEC) may take many forms, from crop raiding and infrastructural damage, though disturbance of normal activities such as travel to work and school, to injury or death of people and elephants (Hoare 2000). HEC occurs throughout the elephant range in Africa, both in forest ecosystems in west and central Africa (Barnes 1996) and savanna ecosystems in east and southern Africa (Thouless 1994; O'Connell-Rodwell *et al*. 2000). HEC is a problem that poses serious challenges to wildlife managers, local communities and elephants alike.

The issue of HEC has become increasingly significant as human populations have expanded and encroached upon elephant habitat (Dublin, McShane & Newby 1997; Hoare & du Toit 1999), particularly where people practice cultivation. Crop raiding is perhaps the most common form of HEC. Although neither the only crop pest in Africa nor the most damaging overall, elephants may cause severe localized damage within affected areas and can destroy entire fields of crops (Barnes, Asika & Asamoah-Boateng 1995; Hillman-Smith *et al*. 1995; Lahm 1996; Naughton-Treves 1998). Moreover, elephants are also dangerous to people. As a result, elephants have a higher profile than other wildlife species and are generally less easily tolerated (Naughton-Treves, Treves & Rose 2000; Hoare 2001).

It is vital, therefore, to gain a thorough understanding of the problem in order to develop and direct mitigation strategies. Recent reviews of HEC (Hoare 1999a, 2000) have identified some trends. Conflict usually takes place between dusk and dawn, and for crop raiding in particular is often strongly seasonal. Spatial patterns have been more difficult to identify. Conflict is generally highest in close proximity to protected areas that act as elephant refuges (Barnes, Asika & Asamoah-Boateng 1995; Bhima 1998; Parker & Osborne 2001). However, few systematic studies of HEC distribution have been conducted.

Other pest species, including carnivores (Stahl *et al*. 2002) and birds (Tourenq *et al*. 2001; Somers & Morris 2002), have exhibited considerable spatial predictability in their patterns of crop and livestock raiding, enabling appropriate management and mitigation methods to be applied strategically. The most comprehensive published study of HEC, however, failed to identify any strong spatial correlates (Hoare 1999a). This suggested that HEC was as much a feature of unpredictable behaviour by male elephants, responsible for the majority of crop-raiding events in the study area in Zimbabwe, as of underlying spatial patterns. This 'male behaviour hypothesis' reflects the fact that male elephants may be more willing to take risks for the higher nutritional rewards of mature crops than female elephants, as has been shown for Asian elephants (Sukumar & Gadgil 1988; Sukumar 1989, 1991).

A similar study in Kenya identified spatial correlates related to human and elephant density. This was partly explained because female-led family groups, which may be more predictable than male elephants, were more involved in crop raiding in this area (Smith & Kasiki 1999). It was not possible, however, to separate incidents caused by male vs. female-led family groups in order to test this hypothesis. Moreover, the study was conducted at a finer spatial resolution than that of Hoare (1999a). Both studies used local government administrative boundaries to delineate areas to be used as data points in subsequent analyses, although those of Smith & Kasiki (1999) were significantly smaller (median = 121 km^2 vs. 448 km^2, Mann–Whitney U = 65, $z = -4{\cdot}86$, $P < 0{\cdot}001$). Aggregating the value of independent variables such as distance from roads, water or protected area boundaries over large and irregular-shaped areas may obscure patterns that would be evident using a more refined spatial delineation of data points. Thus the identification of spatial correlates of HEC intensity in one study and not the other may be as much a result of differences in spatial resolution as of differences in the composition of elephant groups involved in HEC.

The aim of this study was to identify whether spatially explicit predictive models of HEC could be derived from field monitoring and other available data, regardless of the composition of the elephant groups involved. The study tested the alternate male behaviour and data resolution hypotheses for the apparent unpredictability of HEC in earlier studies. This was achieved by performing analyses at fine (1 × 1-km and 5 × 5-km) spatial resolutions and by separating crop-raiding incidents involving all male groups from those involving female-led family groups. The resolution of the analyses was further refined compared with earlier studies by conducting separate analyses on different forms of HEC (crop raiding vs. human deaths and injuries) that may have different spatial patterns. The study tested a simple grid-based geographical information system (GIS) and statistical analytical procedure not previously used in HEC research but with the potential for widespread comparative application.

Materials and methods

Study area

TransMara District lies in the south-west of Kenya on the border with Tanzania (0°50′–1°50′S, 34°35′–35°14′E). The district was created out of the western part of Narok District in 1994 and encompasses the western portion of the world-famous Masai Mara National Reserve (MMNR) (Fig. 1). It covers an area of some 2900 km^2, of which approximately 2200 km^2 is an unprotected area inhabited by people separated from the protected and uninhabited MMNR by a steep escarpment. Elevation outside of MMNR ranges from 1900 to 2500 m and is characterized by a southern

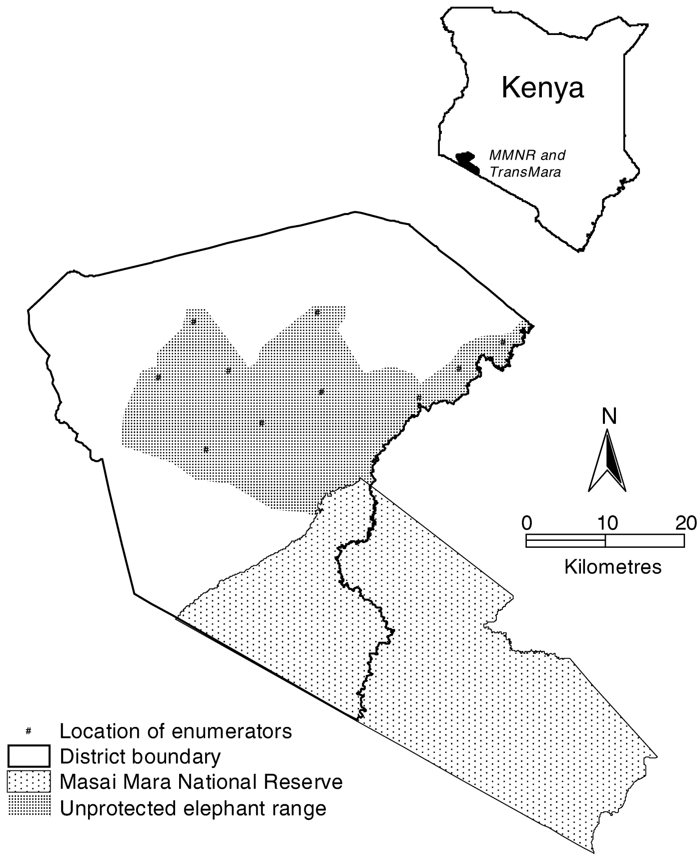

Fig. 1. Map of TransMara District showing the unprotected elephant range outside Masai Mara National Reserve and the locations where local enumerators were stationed. The study covered the whole of the unprotected elephant range.

plateau separated from northern highlands by the Mogor River and drainage system running north-east to south-west. Rainfall averages 1200–1500 mm annually and falls in a bimodal pattern from March to June and from November to December. There is a north–south gradient of high to low rainfall across the district (Sitati 2003).

The natural vegetation is a mosaic of Afro-montane, semi-deciduous and dry-deciduous forests and *Acacia* savanna woodlands (Kiyiapi, Ochieng-Obado & Otieno-Odek 1996). However, the northern, north-east and south-west areas of the district have high agricultural potential, and these areas have undergone significant transformation for cultivation, particularly of maize and sugar cane. The central area has lower potential and remains substantially forested, although it is increasingly affected by slash-and-burn cultivation and charcoal production. The 1999 census recorded 168 721 people living in TransMara District, with particularly dense settlement in the north and west where the traditional, pastoralist Maasai inhabitants have been joined by an influx of other agro-pastoral ethnic groups. Land tenure outside of MMNR is a mixture of private (18%) and communal (group ranch, 82%) ownership.

Elephants once ranged across most parts of TransMara District and beyond. As immigration, human population growth and land transformation have increased around the borders of the district, elephants have become excluded from these areas (cf. Hoare & du Toit 1999). As a result, the elephant range outside of MMNR has gradually contracted to its present area of approximately 1000 km^2 in the centre of the district (Fig. 1). This area supports a resident population of approximately 200–300 individuals that appears to be spatially segregated from the larger population living mainly within MMNR. It has lower rainfall, agricultural potential and human population density than other parts of the district but more intact forest.

The conflict between elephants and people over cultivated crops began with the immigration of non-Maasais into TransMara in the 1920s, through land acquisition and intermarriage with resident Maasai, to exploit the fertile soils and high rainfall. As the cultivation introduced to the District by these immigrants increased, so too did crop raiding, which has become a perennial problem throughout the 1990s. Equally, both humans and elephants have suffered injury and death as a result of their interactions. This TransMara case study therefore represents a model of a common situation across Africa where elephants and people co-exist in disharmony.

DATA COLLECTION

Data were collected on both crop-raiding incidents and human deaths and injuries from March 1999 to August 2000. To establish a reliable and independent conflict reporting system (Hoare & Mackie 1993; Hoare 1999a), a team of 10 community members was selected and trained to enumerate crop-raiding incidents. This circumvents the problem of overexaggeration of reported conflict by farmers themselves (Siex & Struhsaker 1999). Each enumerator was stationed at a different location within the elephant range, to offer widespread coverage of the area. Any crop-raiding incident within an enumerator's area was visited for verification purposes and to record the location in Universal Transverse Mercator (UTM) coordinates using a Garmin GPS12 satellite navigation unit (Garmin Corp., Ulathe, KA). Further details of the incident, such as elephant group size and composition (male groups vs. female-led family groups; cf. Sukumar & Gadgil 1988) and time of incident, were recorded from complainants on a standardized reporting form (Hoare 1999b). Incidents of human death and injury were similarly recorded. However, due to the rarity of such incidents during the survey period, historic incidents from 1986 onwards were also investigated. Details of such incidents were obtained from Kenya Wildlife Service occurrence books and through participatory rural appraisals (PRA) with local communities, and the site of each incident was revisited to record its exact location. The UTM coordinates of each incident were imported into the ArcView v.3·2 GIS software package (ESRI Inc., Redlands, CA) for manipulation prior to analysis. Separate layers were created for crop raiding by male elephants, crop raiding by family groups and human deaths and injuries.

Data for seven independent variables that might determine the spatial pattern of HEC by their effect on human density or elephant density and movement patterns were obtained from a variety of sources. Digital road and river vector files derived from 1 : 50 000 topographic sheets and satellite imagery were obtained from the Organization for German Technical Cooperation (GTZ) in Lolgorien, TransMara District. Digital polygons of farm and forest cover were obtained from the same source and updated with ground surveys in 1999. The locations of market centres were recorded in the field using the Global Positioning System (GPS). A digital elevation model (DEM) was derived from the GTOPO30 data available from the Eros Data Centre, Sioux Falls, SD, USA. Mean human population density in administrative sublocations within the district was obtained from the 1999 population census. No elephant density data were available so this could not be included in the analyses. Instead the analyses were confined to the area of known elephant range where elephants were present for at least part of the year and within which all conflict incidents occurred (Fig. 1; Sitati 2003).

DATA ANALYSIS

To facilitate data analysis, all variables were imported into ArcView and superimposed onto a 1-km^2 grid covering the whole of the elephant range (a total of 966 grid cells). The area of each grid cell comprising forest or cultivation was calculated. The road, river and market centre vector files, and forest polygons, were used to derive raster distance maps at 100-m resolution in ArcView, and mean distance from each of these features was calculated for each 1-km^2 grid cell. The DEM was already at a resolution of 1 km^2 and so did not need to be manipulated. Human population density was at a coarser resolution and so each grid cell was assigned the mean density of the sublocation in which it was located (or the mean of two sublocations where grid cells overlapped sublocation boundaries).

Analysis was carried out using SPSS v.9 (SPSS Inc., Chicago, IL) at the level of the 1-km^2 grid cell. Univariate correlations were conducted using Spearman's rank correlation (r_s) for comparison with Hoare (1999a). Because the intensity of different types of HEC exhibited highly skewed distributions among grid cells it was not possible to use linear regression to identify multivariate correlates. Instead, each type of HEC was binary coded into presence and absence for each grid cell, and analysis was undertaken using multiple stepwise logistic regression (cf. Manel, Williams & Ormerod 2001; Tourenq *et al.* 2001), with entry and exit of variables determined by the Wald statistic with P-values of 0·05 and 0·1, respectively. The relative contribution of variables to the model was estimated by the R statistic (Tourenq *et al.* 2001). Spearman's rank correlation was used to examine the relationship between predicted probabilities of HEC occurrence from the logistic models and actual intensity of HEC in grid cells.

When analysing spatial data there is a danger of non-independence caused by spatial autocorrelation (Koenig 1999) whereby adjacent cells share similar values in the dependent variable. This effect can reduce the degrees of freedom in the analysis and thus increase the chances of type I errors (Legendre & Legendre 1998), whereby correlation coefficients appear more significant than they actually are. We tested for spatial autocorrelation in the dependent variables by calculating Moran's I statistic (Cliff & Ord 1981) using the Crimestats v1·1 software package (N. Levine & Associates, Annandale, VA). The significance of Moran's I was examined using a Z-test. An autocovariate term was derived to model spatial autocorrelation explicitly where it occurred (Augustine, Mugglestone & Buckland 1996). The term used was an inverse Euclidean distance weighted mean of conflict presence in the eight surrounding cells of each cell in the grid. This increases the fit of logistic models where data are spatially autocorrelated and removes spurious variables from the analyses. However, caution is still needed in the interpretation of the significance of correlation coefficients where spatial autocorrelation occurs (Osborne, Alonso & Bryant 2001). For this reason, we also conducted the analyses at a coarser (5 × 5-km grid) resolution at which spatial autocorrelation was less likely to be significant.

Of the 966 1-km^2 grid cells, crop raiding by male groups occurred in 51 cells and by family groups in 91

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cells, whilst human deaths and injuries were present in 34 cells. For each analysis the data were divided randomly into a training set to build the model and a testing set to evaluate its performance (Fielding & Bell 1997; Ambrosini *et al.* 2002). For male crop raiding, the training set comprised 80 cells (40 presences and 40 absences) and the testing set 886 cells (11 presences and 875 absences). For crop raiding by family groups, the training set comprised 100 cells (50 presences and 50 absences) and the testing set 866 cells (41 presences and 825 absences). For human deaths and injuries, the training set comprised 50 cells (25 presences and 25 absences) and the testing set 932 cells (nine presences and 923 absences). The partition into random training and testing sets was repeated five times to avoid any bias in either set (Tourenq *et al.* 2001).

At the 25-km^2 scale only 55 grid cells were available, and so for each analysis the data were divided into a training set of 50 cells and a testing set of five cells (two presences and three absences in each case). The partition was repeated five times in an adapted jack-knifing procedure (Suárez-Seoane, Osborne & Alonso 2002), with a unique set of five testing cells chosen at random each time from those not chosen in previous partitions. In this way a testing set of 25 cells was created from five separate analyses. Model performance on the testing sets was evaluated by calculating the area under the curve of receiver operating characteristics (ROC) plots (Pearce & Ferrier 2000). ROC values range from 0·5 to 1·0. Values above 0·7 indicate a good model fit while those above 0·9 indicate a highly accurate model (Swets 1988).

Results

CHARACTERISTICS OF ELEPHANT CROP RAIDING

Elephants in TransMara destroyed a variety of crops including maize *Zea mays* L., millet *Eleusine coracana* L., sorghum *Sorghum vulgare* Pers., cassava *Manihot esculenta* Crantz., banana *Musa domestica* L., sugarcane *Saccherum officinarum* L., tomato *Lycoposicon esculentum* Mill., kale *Brasica* spp., pumpkin *Curcubita maxima* Duch., potato *Ipomea patatas* L., tobacco *Nicotina tobacum* L. and bean *Phaseolus vulgaris* L. A total of 329 crop-raiding incidents was recorded between March 1999 and August 2000. Crop raiding occurred exclusively during the hours of darkness from 19:00 to 05:00 h, with a peak at 22:00 h. In accordance with previous studies (Hoare 1999a), the size of crop-raiding elephant groups ranged from 1 to 40 (median = 6), with 80% in groups of ≤ 10 animals. However, in contrast to Hoare (1999a), only 2% of incidents involved lone male elephants. Individual males and male groups carried out 32% of incidents (n = 105, median group size = 3, range = 1–9) compared with 79% in Zimbabwe (Hoare 1999a), while 68% were by family groups (n = 224, median group size = 8, range = 3–40).

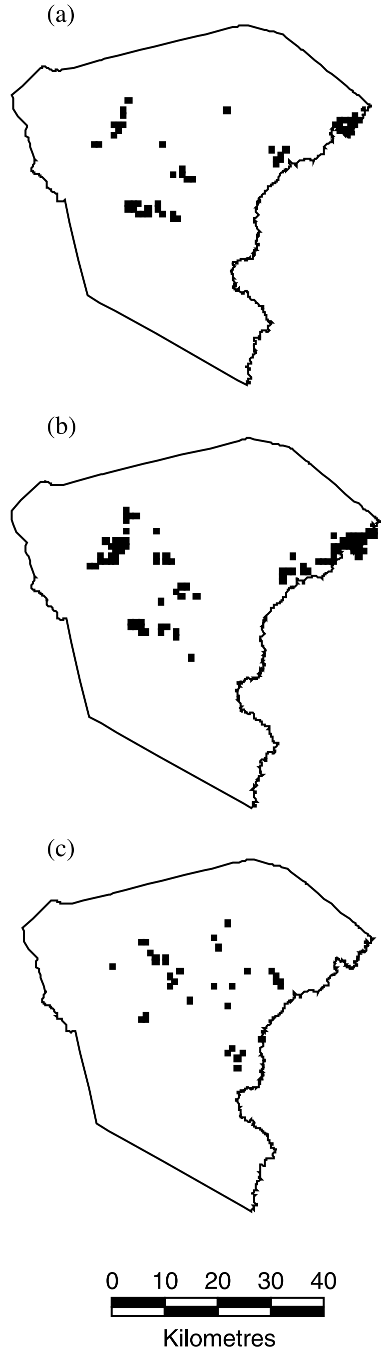

Fig. 2. The occurrence of HEC in 1-km^2 grid cells in TransMara District: (a) crop raiding by all-male groups; (b) crop raiding by female-led family groups; (c) human deaths and injuries caused by elephants.

SPATIAL PATTERN OF CROP RAIDING

Crop-raiding incidents were highly clustered at the 1-km^2 scale (Fig. 2a,b) and exhibited significant spatial autocorrelation (Moran's I = 0·02 and 0·03 for male crop raiding and family group crop raiding, respectively; P < 0·0001 in both cases). As a result, the significance of correlation coefficients in subsequent analyses at this spatial resolution may be overestimated and so are not stated (cf. Balmford *et al.* 2001).

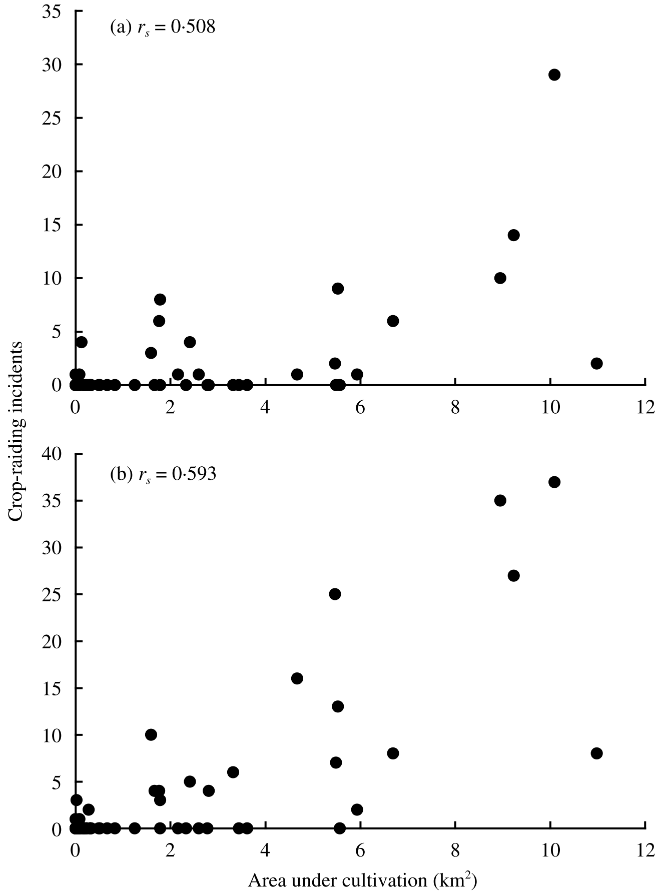

Fig. 3. The relationships between crop-raiding intensity and area under cultivation in 25-km² grid cells: (a) all-male groups; (b) female-led family groups.

Table 1. Spearman's rank correlations for associations between nine variables and either male elephant crop raiding, family group crop raiding or human deaths and injuries, in 25-km² grid cells (n = 55 in all cases). *P < 0·05, **P < 0·01, ***P < 0·001

	Crop raiding		
Variable	Male	Family group	Human deaths and injuries
Autocovariate	0·184	0·408**	0·065
Area of cultivation	0·508***	0·593***	0·046
Distance from towns	–0·424**	–0·311*	–0·210
Human density	0·319*	0·277*	0·007
Area of forest	–0·147	–0·265	0·014
Elevation	0·045	0·068	–0·038
Distance from roads	–0·188	0·017	–0·270*
Distance from rivers	–0·204	–0·114	–0·123
Distance from forest	–0·038	0·110	–0·142

Correlations of crop-raiding intensity with independent variables were generally weak (r_s = 0·01–0·32), especially when compared with correlations with the autocovariate terms (r_s = 0·446 and 0·542 for male and family groups, respectively). Equally, the best predictor of the occurrence of crop raiding in logistic regressions at this resolution was the autocovariate term (median R = 0·382 and 0·432, respectively). ROC values for these models ranged from 0·86 to 0·95 for male groups and 0·92 to 0·95 for family groups.

At a 25-km² resolution, spatial autocorrelation was not significant (Moran's I = −0·003 and 0·013 for male and family groups, respectively; P > 0·1). Thus an examination of the significance of spatial correlations at this scale could be conducted with confidence.

The area under cultivation was positively correlated with the intensity of crop raiding by both male and family groups (P < 0·001; Table 1 and Fig. 3). Male elephant crop raiding was also negatively correlated with distance from towns (P < 0·01).

Logistic regressions generated significant spatial models for the occurrence of crop raiding (Table 2). Crop raiding by male groups was predicted by area under cultivation and proximity to towns (ROC = 0·83 ± 0·09).

Table 2. *R*-values for variables included in logistic regression analyses of crop raiding at the 25-km² scale. Each analysis was repeated five times with different training sets to generate samples of *R*-values from which to calculate the values given in the table

	Male		Family group	
Variable	Median	Interquartile range	Median	Interquartile range
Area of cultivation	0·271	0·254–0·363	0·344	0·334–0·349
Distance from towns	–0·186	–0·233–0·000	NS	NS

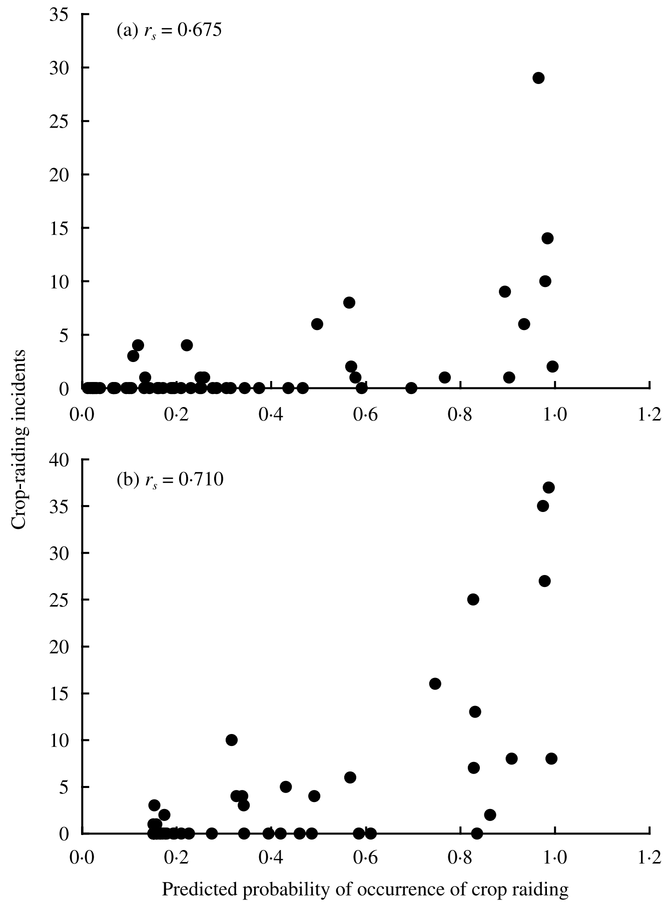

Fig. 4. The relationships between predicted probability of occurrence of crop raiding, from logistic regression models, and actual intensity of crop raiding in 25-km² grid cells: (a) all-male groups; (b) female-led family groups.

Crop raiding by family groups was predicted by area under cultivation alone (ROC = 0·95 ± 0·05). Including an autocovariate term did not alter the other variables in the model nor improve model performance. Moreover, the predicted probabilities of occurrence of both male and family group crop raiding were significantly positively correlated with the intensity of each type of crop raiding (r_s = 0·675 and 0·710, respectively; n = 55, P < 0·001 in both cases; Fig. 4).

HUMAN DEATHS AND INJURIES

In total, 35 incidents of human death (n = 21) and injury (n = 14) were recorded between 1986 and 2000. More than 50% of these occurred in the 5 years from 1996 to 2000, and almost all cases occurred during the hours of darkness.

Human deaths and injuries were less clustered than crop-raiding incidents (Fig. 2c) but spatial autocorrelation was still significant at the 1-km² resolution (Moran's I = 0·004, P < 0·01). As with crop raiding, correlations of the intensity of human deaths and injuries with independent variables were weak (r_s = 0·02–0·24) and the best predictor of the occurrence of human deaths and injuries was the autocovariate term (median R = 0·250, ROC = 0·73–0·86).

At a 25-km² resolution, spatial autocorrelation was not significant (Moran's I = −0·016, P > 0·1). The intensity of human deaths and injuries at this scale was negatively correlated with distance from roads (P < 0·05; Table 1 and Fig. 5) but in general correlations with independent variables were weaker than for crop raiding. No logistic model for the occurrence of human deaths and injuries could be constructed.

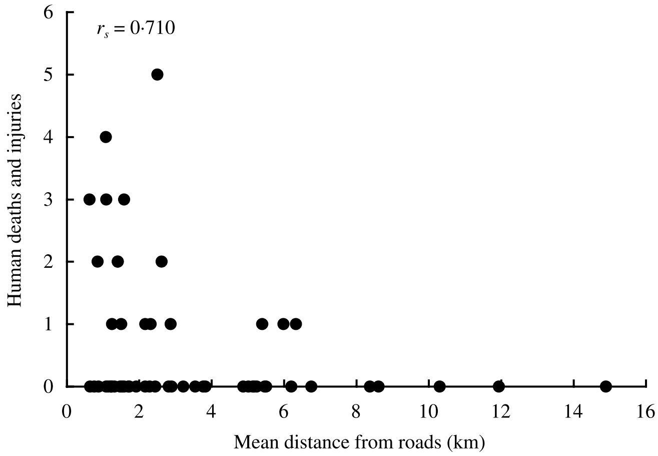

Fig. 5. The relationship between the intensity of human deaths and injuries and mean distance from roads in 25-km^2 grid cells.

Discussion

This study is the first of its kind to compare the spatial patterns of different types of HEC. Furthermore, it is the first to use a systematic, grid-based approach to analyse spatial patterns. The occurrence of HEC and its intensity were correlated with a variety of underlying spatial variables in TransMara District. The study identified different correlates of crop raiding and human deaths and injuries. Moreover, it was possible to develop predictive models of crop raiding by both male elephant groups and family groups, suggesting that male elephants are no less predictable than females.

There are, however, some caveats to this conclusion. Although crop raiding by both male and family groups was significantly correlated with the area of each grid cell under cultivation, that by male groups was also significantly correlated with proximity to towns. Since proximity to towns also reflects increasing human density on a fine scale, crop raiding close to towns is more likely to bring elephants into contact with people. Thus, this relationship with crop raiding by male elephants, but not by family groups, would seem to indicate an increased propensity to take risks by male elephants (Sukumar & Gadgil 1988). This in turn is more likely to lead to less predictability in male elephant behaviour. Indeed, although significant correlations were identified, those for male crop raiding were less strong than those for family groups, and the predictive performance of resulting spatial models was less accurate for males. Although possibly due to differences in prevalence of male vs. family group raiding, this might nevertheless suggest that all-male groups are indeed less predictable than female-led groups.

It may be the case that single males are even less predictable, so that an area with a higher proportion of single males involved in HEC (e.g. Hoare 1999a) may reveal few if any spatial correlates. However, results from elsewhere with a high proportion of single bull elephants involved in HEC do not support this (Smith & Kasiki 1999). It seems more likely that data resolution, and not elephant group composition, is the key to identifying spatial correlates of HEC.

The pattern of human deaths and injuries was less predictable than that of crop raiding. This is partly because such events were less frequent but may also be due to the fact that underlying variables, including human and elephant population density and distribution, forest cover and road networks, may have changed over the 15-year period for which data were available. The correlation with proximity to the current road network reflects the fact that such events usually occurred at night when people were travelling to or from home along main roads. They represent unfortunate spatial coincidences when elephants have ventured out of forest refuges and crossed roads just as people were passing by. In around one-third of cases the human victim had been drinking and was returning home from a local bar. Despite the fact that no predictive model of the occurrence of human deaths and injuries could be constructed, there is still a recognizable spatial pattern to the intensity of incidents. The fact that this pattern was different to that of crop raiding implies the need to ensure separation of these types of HEC in future analyses.

At the 1-km^2 resolution crop raiding and, to a lesser extent, human deaths and injuries were spatially clustered. Such localized and persistent elephant crop raiding has been witnessed elsewhere (Bell 1984; Damiba & Ables 1993; Naughton-Treves 1998). Part of this reflects clustering in the underlying variables such as area under cultivation and distance from roads. Part of it may reflect proximity to particularly dense elephant refuges, from which they forage at night. Neither area of forest nor distance from forest margin predicted the occurrence or intensity of HEC in our study. However, these may not be accurate indicators of daytime elephant refuges as elephant density data over the study area were not available so could not be included in the analyses. Indeed, local communities reported particularly high elephant densities in refuges close to three of the major conflict areas. Clustering of crop-raiding incidents may also reflect the fact that elephants have long memories (McComb *et al*. 2001) and often utilize traditional movement routes (Low 2000) and thus may return to areas where they remember having successfully raided in the past. The role of daytime refuges and corridors in determining the distribution and intensity of HEC outside protected areas warrants further study.

Clustering notwithstanding, there were clear relationships with underlying spatial variables that became more apparent at the coarser-scale analyses. Although useful for fine-scale mapping of HEC and identification of high conflict zones, data at the 1-km^2 resolution exhibited too much noise and autocorrelation to identify spatial correlates reliably. At the 25-km^2 resolution, the data were less clustered and so spatial correlates could be identified with statistical confidence. Moreover, those variables identified as important at this resolution were also those with the strongest correlation coefficients at the 1-km^2 resolution. This suggests that a compromise in resolution on statistical grounds does not affect the identification of underlying relationships and may improve clarity by reducing noise. Although coarser than the 1-km^2 resolution data, the 25-km^2 resolution data are still considerably finer overall than the government administrative units used in previous analyses (Hoare 1999a; Smith & Kasiki 1999; although the latter ranged from 9 to 426 km^2 the median of 121 km^2 was considerably coarser than in this study). It is also the finest resolution available for some data sets, such as wildlife and livestock aerial counts (Ottichilo *et al*. 2000), that may be incorporated into spatial analyses. It is therefore recommended that a 25-km^2 grid is used to generate spatial units for HEC analysis. When combined with a suitable index of HEC intensity (Hoare 1999a) such a grid would be a useful comparative mapping tool that could be applied to areas experiencing HEC throughout Africa.

A grid-based approach to mapping, combined with robust statistical models of HEC, could also be used to predict HEC intensity in other areas or under changing circumstances. Although logistic models simplify the data into presence and absence, the correlations between predicted presence and actual intensity suggest that relative intensity can be inferred using logistic models. Moreover, the models developed in this study relied solely on variables such as land cover and distance from roads and settlements that can be easily and inexpensively derived from remotely sensed data, topographic maps and simple ground-truthing. This is in contrast to variables such as human and elephant density that would require considerable time and resources to measure at such fine spatial scales. Such models could easily be developed using the same variables at the same fine scale resolution in other sites to enable a more meaningful comparative assessment of factors affecting HEC across the continent than has been possible to date. Including some reference to locally recognized daytime elephant refuges and traditional movement routes may also increase the strength of these analyses. When combined with a grid-based GIS, such models could be useful management tools both for planning the deployment of mitigation methods and for future land-use planning as any planned changes can be incorporated into the models to assess vulnerability.

For example, although the risk of human death and injury is small it can probably be reduced substantially with the avoidance, at night, of walking in areas of high risk, even along main roads. Crop raiding clearly increases with increasing settlement and cultivation up to a threshold at which elephants are permanently excluded (Hoare & du Toit 1999; Smith & Kasiki 1999). Moreover, the existence of discrete crop-raiding zones may simplify mitigation strategies by enabling measures to be focused on the 'front line' of farms closest to elephant refuges (Bell 1984; Sukumar 1989). A range of traditional, non-fatal methods has been used by communities all over Africa to combat crop raiding. These include guarding, scaring elephants with light, noise and smoke and erecting barriers (Hoare 1995, 2001). Although not 100% effective and subject to habituation (Bell 1984; Tchamba 1996), focusing a shifting combination of such methods on the front-line farms may be the most successful short-term approach to mitigating this most prevalent form of HEC. Equally, knowing where to target mitigation measures also allows for the strategic implementation of early warning systems that are critical to the success of HEC mitigation. Comprehensive field tests of the efficacy of such measures are vital to identify the most appropriate combination.

Wherever people and elephants coincide, however, HEC will occur. Short-term mitigation can only reduce, and not eradicate, the problem (O'Connell-Rodwell *et al*. 2000). In TransMara the areas of highest agricultural potential have already been settled extensively and transformed, and this historic elephant range has been sacrificed. Settlement and cultivation are now encroaching on the remaining elephant range, resulting in further HEC. A longer-term solution to the problem would be to avoid cultivation or extensive settlement within the remaining elephant range. The Maasai occupants of the area, who still form the majority, were not traditionally agriculturalist and some communities have now begun to approach the issue of alternatives to cultivation to alleviate conflict.

Tourism is viewed as a significant untapped opportunity outside of MMNR, within which a large existing potential client base resides. Elsewhere in Kenya, communities are developing small-scale tourism as a wildlife-compatible land use that generates direct economic benefits from wildlife (Leringato 2001; Ogutu 2002). For example, communities in Mwaluganje near Mombassa have abandoned cultivation and settlement in an elephant corridor between protected areas and, with the assistance of the Kenya Wildlife Service, have developed an elephant sanctuary that generates entrance fee revenue from tourists. Communities in TransMara bear the costs of living with wildlife without receiving many of the benefits from tourism in MMNR (Walpole & Leader-Williams 2001). They are now beginning to take it upon themselves to organize community associations charged with exploring and developing alternatives to cultivation that conserve the remaining forest whilst generating benefits from both forest and wildlife. Generating direct tourism benefits from elephants in a low-density, forested area may be difficult in the absence of trophy hunting, which is not permitted in Kenya but which can offer considerable benefits to offset the costs of co-existence (Taylor 1993; Leader-Williams, Smith & Walpole 2001). However, any alternative to cultivation, such as broader wildlife-based and cultural tourism, will alleviate HEC and render co-existence all the more tolerable.

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