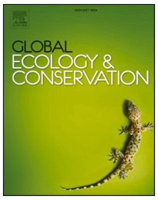
Global Ecology and Conservation 54 (2024) e03068

Contents lists available at ScienceDirect

Global Ecology and Conservation

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



Original research article

# Deforestation and water availability as main drivers of human-elephant conflict

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ARTICLE INFO

*Keywords:*
Human-wildlife conflict
*Loxodonta africana*
Plant preferences
Global change
Climate change
Crop damage
Prediction

ABSTRACT

Climate change, land use conversion and human population growth are reducing and fragmenting historical ranges of large animals, especially in Africa. Particularly, land conversion to agriculture is leading to coexistence challenges between humans and elephants. In this study we investigated the factors affecting the intensity of elephant crop damage in the Selous-Niassa Wildlife Corridor (Tanzania). We also predicted future conflicts (crop damage intensity) for different land management (crop types) and water scarcity (drought) scenarios using model averaging. Our results show that intensity of elephant damage (proportion of area damaged in an individual farm as a percentage) increased with crop palatability and land use conversion in the last ∼30 years, particularly deforestation. Conversely, the intensity of elephant damage decreased with increasing human activity (higher proportion of settlements and farmland), and distance to waterbodies. Most farms affected by elephants (65 %) were at short distances (< 250 m) from waterbodies. We also predicted a significant increase of elephant crop damage intensity from 17 % when the farm is covered with no palatable crops, to 54 % and 63 % when palatable crops covered 50 % and 100 % of the farmland, respectively. For the predicted water stress scenario in which all small seasonal waterbodies would dry off, we predicted a 46 % reduction in the total area of farmland susceptible to damage although we expect an increase in human-wildlife competition for water. We conclude that land use changes and water availability strongly affect elephant crop damage. We hope these results contribute to the development and better implementation of management strategies that enhance long-term peaceful coexistence between humans and elephants.

## 1. Introduction

Human population growth and anthropogenic activities are producing important changes in the global environment, causing among other effects, climate warming and altered precipitations, land use changes and over-exploited natural resources (Sage, 2020). These changes commonly named as Global Change are affecting biodiversity and are threatening numerous species with extinction. In particular, land use transformation, due to its broad scale, is considered the leading cause of biodiversity loss (Vermaat et al., 2017).

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https://doi.org/10.1016/j.gecco.2024.e03068
Received 29 February 2024; Received in revised form 12 June 2024; Accepted 30 June 2024

Today, human population in Africa is undergoing a great demographic and geographic expansion (Kaba, 2020; Potapov et al., 2022). Additionally, Africa stands out disproportionately as the most vulnerable region to climate change in the world (Sylla et al., 2018; Rao et al., 2020; Williams et al., 2021), which is particularly worrying as it is home to many biodiversity hotspots and unique species (Ayeni et al., 2023). In particular, predictions for East Africa foresee an increase in aridity (Seitz and Nyangena, 2009; Dai, 2011). The predicted increase towards moderate to severe droughts (Haile et al., 2020), might represent an important hit on both threatened animal populations and local farming communities. Overall, it is estimated that the overexploitation and degradation of biodiversity will result in the loss of 50 % of Africa's bird and mammal species (UNEP-WCMC, 2016).

Due to their body size, slow reproduction rate, strong water dependency and broad home ranges, African savanna elephants (*Loxodonta africana*, Blumenbach 1797) are an emblematic example of the new challenges facing global change (Martínez-Freiría et al., 2016). The International Union for Conservation of Nature (IUCN) categorizes the species as endangered, highlighting four main threats for the survival of the species: land use change (Boult et al., 2019), climate change (Martínez-Freiría et al., 2016), coexistence challenges between elephants and humans due to competition for natural resources (Sitati et al., 2003; Songhurst, 2012; Mariki et al., 2015) and poaching (Douglas-Hamilton, 1987; Chase et al., 2016). Additionally, human population growth and expansion is exacerbating this unfavourable environment, by reducing and fragmenting elephant habitats and historic ranges (Ripple et al., 2015) and, thus, increasing the intersection of human activities and elephants ́ ranges (Hoare, 1999).

Rivers and other waterbodies represent important elephant congregation areas as they provide suitable habitats, foraging areas and water supply (Smit et al., 2007; Harris et al., 2008; Haynes, 2012). Although food availability is a key factor explaining elephant movements (Bohrer et al., 2014; Boult et al., 2018), the lack of drinking water and wooded shelter represent important limiting factors (Boult et al., 2019), that make elephants even more vulnerable to climate and land use changes. Other factors determining elephant movements in the landscape are topography (Wall et al., 2006), perceived risk (Graham et al., 2009; Ihwagi et al., 2018), social companionship (Goldenberg et al., 2016) and site fidelity (Loarie et al., 2009). Site fidelity, particularly of females (Pinter-Wollman, 2009; Loarie et al., 2009), might influence the exploratory behaviour of the herds (Druce et al., 2008), restricting their ranges to the historically used areas that might have been transformed into cultivated land in recent times. On the other hand, elephants inhabiting wooded ecosystems have historically preferred open and dense woodland over grassland (Matzke, 1971) as they provide not only forage areas but a preferred shelter from high temperatures during the day (Kinahan et al., 2007) and against humans (Kioko et al., 2008).

Coexistence challenges between humans and elephants, although have occurred during centuries, have dramatically increased in recent years due to the expansion of land needed for agriculture. Crops can represent an important nutritional source for elephants (Rode et al., 2006; Chiyo et al., 2011; Vogel et al., 2020) and can be preferred over natural vegetation due to their higher nutritional and mineral value, reduced chemical defenses and high water retention (Chiyo et al., 2005; Ogunjobi et al., 2018). In addition, the majority of agricultural crops ripen and increase in quality at the onset of the dry season when green grass dries off and loses quality (Vogel et al., 2019 and, 2020), becoming an attractive alternative food source (Osborn, 2004; Vogel et al., 2020). From an ecological and ethological perspective, numerous studies have concluded that elephants prefer some crops over others (Naughton-Treves, 1998; Walpole et al., 2004; Malugu et al., 2011; Montero-Botey et al., 2021). However, not all farms are affected in the same way and crop damage patterns have also been associated with human population density (Newmark et al., 1994), proportion of cultivated land (Pozo et al., 2017) and road networks (Sitati et al., 2003). Previous studies have also shown that the proximity to forest cover and protected areas increases the vulnerability of a farm to be affected by elephants (Nyhus and Tilson, 2000; Graham et al., 2010; Guerbois et al., 2012; Wilson et al., 2013; Chen et al., 2016). Thus, forest patches can act as safe staging areas for elephants before and after entering in crop lands (Tiller et al., 2021; Hahn et al., 2023).

Elephant presence in farms may represent not only important economic loses (Graham et al., 2010) but also, in some cases, the loss of human lives (Fisher, 2016). Frequent incidents can lead to a reduction of local communities' tolerance towards wildlife, strengthening negative attitudes towards conservation efforts (Dickman, 2010; Goswami and Vasudev, 2017) and even fuelling retaliation killings of wildlife (Linkie et al., 2007). Therefore, mitigating human-elephant coexistence challenges becomes imperative to ensure long term elephant conservation (Karidozo and Osborn, 2015).

In order to guide conservation actions, we need to increase our understanding of the main historic and current drivers affecting the occurrence and intensity of elephant damage on the farms across space and time. In this study we aimed to investigate the factors that influence the intensity of elephant crop damage on individual farms in the Selous-Niassa Wildlife Corridor (in southern Tanzania), that forms part of one of the largest and most paradigmatic Trans Frontier Conservation Areas in Africa. To do that, we considered not only the effect of different land use types and water availability, but also crop preferences of elephants and historic site fidelity, thus exploring behavioural, spatial and socio-ecological factors together for the first time. As a highly applied study, we assessed the probability of crop damage for each farm and predict future elephant damage for different management schemes (crop types) and climate (drought) scenarios. We expect our results and model forecast may contribute to a better implementation of management strategies and help enhance long-term peaceful coexistence between humans and elephants.

## 2. Materials and methods

### 2.1. Study area

The study area is located in the Selous-Niassa Wildlife Corridor, a conservation area made up of five Wildlife Management Areas (WMAs) and 30 villages, that links Julius Nyerere National Park (former Selous Game Reserve) in Tanzania with Niassa National Reserve in Mozambique. The study villages (Fig. 1) are in the northern part of the corridor, bordering Julius Nyerere National Park

(Rahaleo, Nambecha and Kajima village), and in the southern part (Mpanji and Msiaje) bordering Sasawala National Forest Reserve. These villages belong to three Wildlife Management Areas (Mbarang'andu, Nalika or Chingoli WMA) but also contain other areas under diverse figures of protection (i.e. local sacred forest, village forest reserves) which borders are not yet officially demarcated and converge with WMAs borders, hosting resident wildlife (Bluwstein and Lund, 2018; MCDI, 2018). The most populated village in 2019–2020 was Nambecha (~4000 people), followed by Rahaleo (~2930 people), Msiaje (~2250 people), Kajima (~1630) and Mpanji (~1100 people) with an average of ~4.3 people/household (Tanzania National Census 2012 & 2022). Local communities mostly base their economy on subsistence traditional (non-irrigated) agriculture of maize, rice and cassava although there are some areas where individual farmers also cultivate cash crops such as cashew nut trees, tobacco, pigeon peas, sesame, etc. Most of the farms cover between 0,5–3 ha of mixed crops (Montero-Botey et al., 2021). Most crops are planted in November (beginning of the rainy season) and harvested in March, extending to August depending on the crop type, except for cashew-nuts that are harvested in October-November (Montero-Botey et al., 2023). In recent years, there has been an increase of pastoral livestock keepers coming from other parts of the country (Mwambene, 2014; Jew et al., 2017) and a higher demand on hard wood (Charnley et al., 2022) and mining (Vertriest et al., 2019; Rweyemamu and Kim, 2020) along the corridor surroundings that have been important assets for the historical economy of this area (Vertriest et al., 2019).

The corridor is a continuous miombo woodland ecosystem, with high spatial variation in plant composition. Elevation ranges from 460 m (in Ruvuma River) to 1284 m asl (in Mtungwe Hill). Mean annual rainfall also varies along the corridor, with a warm rainy season (mid-November-mid May) of around 1250 mm in the northern part, decreasing to 800 mm along the Ruvuma River, where savannah woodlands with baobab trees (*Adansonia* spp.) are found (Baldus and Hahn, 2009). The area harbours important populations of wildlife, in particular an elephant population of 602 ± 258 individuals with higher density in the northern part (TAWIRI, 2019). It also covers traditional migratory routes of elephants, forming part of one of the world's largest trans-frontier conservation areas (Mpanduji, 2004). Formerly, the corridor together with Niassa and Selous ecosystems was an important source of poached ivory between 2006 and 2016 (Chase et al., 2016), reaching its highest peak between 2009 and 2013 (Bennett, 2015). In addition, reports of Tunduru District recorded 49 elephants killed by district rangers from 2004 to 2014, due to human-elephant conflicts such as damages to crops or elephant charges at humans (unpublished data). Since 2016, the continuous effort on law enforcement and community awareness have reduced elephant mortality due to poaching or conflict (TAWIRI, 2019; TAWIRI, 2024). However, the exponential expansion of farmland and deforestation have produced an increase of human-elephant coexistence challenges mostly due to the presence of large herds of elephants in the area over the last years (Montero-Botey et al., 2022). In contrast with other studies suggesting that mainly bull elephants damage crops (Hoare, 1999; Sitati et al., 2003; Graham et al., 2010; Chiyo et al., 2011 and, 2012;

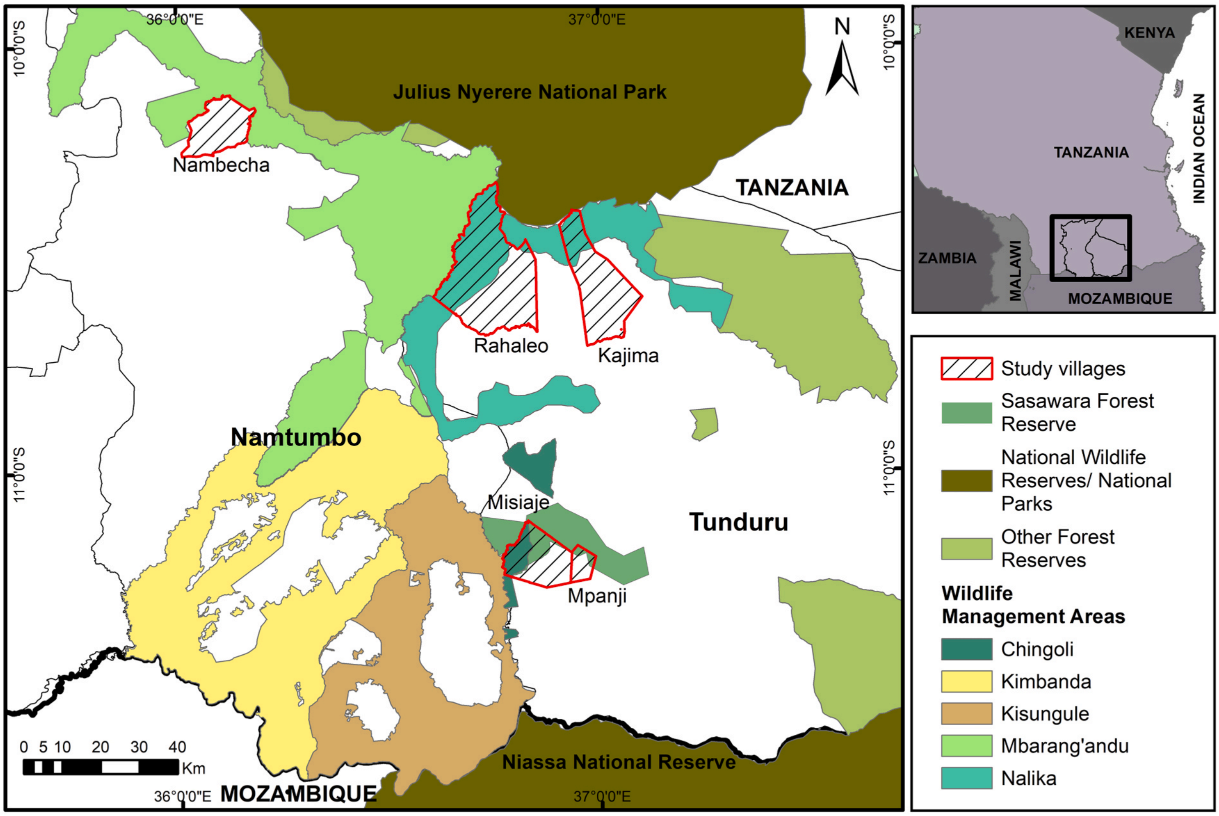


**Fig. 1.** Location of the study villages. Selous-Niassa Wildlife Corridor, Tanzania.

Smit et al., 2019), in the study area crop damage is mostly caused by big herds of female elephants and their calves (Montero-Botey et al., 2021) as observed in other areas of East Africa (Smith and Kasiki, 2000; Tiller et al., 2021).

In the Selous-Niassa Wildlife Corridor, farmers and rangers consider elephants to be the most problematic animal, affecting more than 50 % of the households at least once over the last 15 years (Montero-Botey et al., 2022). Although chili fences (Graham and Ochieng, 2008) have been used in some farms along the corridor encouraged by government institutions and NGOs, the most common mitigation measure applied in the area is guarding the crops at night and making noises to chase them away (drumming, clapping, shouting, etc.). Other mitigation measures such as planting non-palatable crops (Matsika et al., 2020) and beehive fences (King et al.2009) are not common in the area although local communities consider them useful and are open to apply them in the future (Montero-Botey et al.,2022).

## 2.2. *Data collection*

### 2.2.1. *Elephant damage incidents*

In each village, one Village Game Scout (VGS) was appointed as an enumerator of all the incidents regarding elephant presence between August 2019 and August 2020. The enumerators were selected for their knowledge of the area and the wildlife movements as well as their official involvement in chasing away elephants from the village. They were appointed in agreement with the village leaders to ensure they were informed of every incident reported, and equipped with a Garmin Etrex10 Global Positioning System (GPS). Each farm affected by elephants was visited as soon as possible (preferably the same day but not later than 7 days after) by filling out a form (Appendix S1) and recording the GPS coordinates of the farm, the area cultivated for each crop type (i.e., each crop species) and the visual estimation of the area damaged by elephants for each crop type. Every enumerator also recorded the GPScoordinates of elephant tracks, when found, and included their land use category. Finally, they also recorded the GPS coordinates of any waterbody in the villages and reported the date they dried off, if so. To ensure a rigorous data collection, the enumerators were trained by two co-authors (MM-B and EK), and the data were checked in the farms (*in situ*) by the authors every month at the beginning of the data collection (from August 2019 to December 2019) and every three months from January to August 2020 (due to COVID-19 prevention). A total of 904 farms were visited.

Additionally, the author MM-B visited 222 farms affected by elephants across the whole corridor (in the five study villages and neighbouring villages) between April and August 2019, collecting the same type of data (Appendix S1), but avoiding overlap with the enumerators in the same villages at the time they were collecting data.

### 2.2.2. *Land use data*

To understand the changes in land use over the last decades we compared the land use maps for years 1990 and 2017, obtained from the Frankfurt Zoological Society (FZS). These maps were created by machine learning from satellite images with pixels of 30x30m during the dry season, fixed and validated with in-situ information by FZS. For both maps, land use was categorized into seven types: grassland, bushland, open forest, closed forest, thickets, farms -settlements- bare land and waterbodies. Unfortunately, these maps did not cover Nambecha village, but were used because it was the most accurate and updated information available for the area. The main river shapefile was provided by World Wide Fund for Nature (WWF) and combined in a new shapefile with information from Landsat orthophotos from June 2019 (Landsat-8, obtained from LandViewer; USGS, 2019) together with the data provided by the enumerators about waterbodies, seasonal rivers and streams.

## 2.3. *Data analysis*

All data were analysed with R.4.1.1. (R core team, 2022) and ArcMap 10.6.1 (ESRI, Redlands, CA, USA).

### 2.3.1. *Crop preference by elephants*

We estimated crop preference using the selection ratio ($w_i$) (Manly et al., 2002), calculated as $w_i = o_i/\pi_i$, where $o_i$ is the proportion of the area used by elephants (i.e. proportion of each crop i with damage) and $\pi_i$ is the proportion of available resources in the environment (i.e. proportion of each crop *i* in each farm). We classified each crop type according to its selection ratio as: low preference when $w_i \leq 0.75$; medium preference when $0.75 < w_i < 1.25$, and high preference when $w_i \geq 1.25$. For relative comparison we also calculated Manly's standardized selection ratio ($B_i$) (Manly et al., 2002). More details of this procedure can be found in Montero-Botey et al. (2021). Unfortunately, in 71 out of the 904 farms visited by the enumerators, the time between the visit and the date of damage was too long to assess the damages properly and those farms were not used in the analysis. However, the separate data from the corridor comprising 222 farms were added to the analysis. Therefore, a total of 1055 farms were used for crop preference analysis (Appendix S2).

### 2.3.2. *Damaged farms and elephant presence*

We used the information provided by the enumerators (904 farms) to obtain the number of farms and people affected by crop damage due to elephants in each village. We also compared elephant presence in the farms (number of days obtained from the enumerators data) and the mean intensity of damage (proportion of area damaged in a farm as a percentage) per village.

### 2.3.3. *Land use change*

We calculated the degree of farmland increase (area devoted to agricultural practices), deforestation and loss of waterbodies in each village for the period 1990–2017. For each farm affected in 2019–2020, we calculated, for 1990 and 2017, the percentage of area covered by the different land use categories in a circular buffer of 1 $km^2$ around the GPS coordinates of the centre of the farm and the Euclidian nearest distance from the centre of the farm to waterbodies. All these spatial calculations were made using spatial analyzing tools in ArcGIS (version 10.6.1; ESRI), based on the FZS land use map. Nambecha village was excluded from this analysis due to the lack of land use information.

### 2.3.4. *Analysis of intensity of crop damage*

To analyse how land uses around the farm influence the intensity of elephant crop damage in each farm, we used beta regression models (Cribari-Neto and Zeileis, 2010) in R software environment (R core team, 2022), where the proportion of crop area damaged by elephants in each farm was the response variable (hereafter, intensity of damage). Fixed effects (predictors) were: (1) Percentage of area covered by farmland, bareland and settlements in the circular 1 $km^2$ buffer around the farm in 2017; (2) Percentage of area covered by open forest in 2017 in the 1 $km^2$ buffer around the farm; (3) Percentage of area covered by closed forest in 2017 in the 1 $km^2$ buffer around the farm; (4) Euclidean distance from the sampled farm to the nearest waterbody; (5) Relative abundance of highly preferred crops (area covered by preferred crops divided by the total area of each farm), although rare or very infrequent crops (present in <10 farms) were not considered in the modelling; and, (6) Percentage of area covered by thickets, open and closed forest (where elephants typically take shelter) in 1990 in the 1 $km^2$ buffer around the farm. Land use data in 1990 was included to explore the possible effect of elephant site fidelity and natal philopatry (Pinter-Wollman, 2009; Loarie et al., 2009) of their previous ranging areas that are now converted into farmland. Although several studies have pointed out distance to protected areas as an important factor influencing crop damage intensity by elephants (as elephant crop damage is more intense within 5 km from protected areas- Gubbi, 2012; Guerbois et al., 2012; Tiller et al., 2021) we decided not to include them because 1) the existence of not yet officially demarcated protected areas (i.e. local sacred forest, village forest reserves), 2) most of the affected farms are located at <5 km away from a WMA or forest reserve, and 3) all the protected areas (officially demarcated or not) are covered by open-closed miombo forest therefore the proportion of forest in 1 km2 around the farm is highly correlated with the distance to protected areas.

For this analysis we used land use data and the data collected by the enumerators in a total of 590 farms with precise and complete GPS coordinates. The beta regression maximal model (containing all the predictors) was standardized with the function scale in R. To make stronger inferences as there were low to moderate levels of collinearity between our predictors, we used the model averaging approach to summarize all the competing models and gain stability (Freckleton, 2011). The model averaging considers multiple competing models as the best fit instead of a single best model (Grueber et al., 2011). We used the dredge function and the model.avg function of the MuMIn package (Barton, 2023) in R for model comparison and to obtain the importance of each predictor (from 0 to 1) respectively. Finally, we selected the group of models with lowest AIC that hold 95 % of the weight and used it for making predictions. To present the results of the regression we created graphs in the ggplot library of R, using the predicted values of the model averaging selection.

### 2.3.5. *Predictions of crop damage intensity under different scenarios*

In order to predict the damage intensity in each farm under different future scenarios, we first created a grid of points separated by 100 meters inside the area identified as farmland, settlements or bareland in 2017, and calculated the predictors 1–6 (described above) for each point with spatial analysis tools in ArcGIS 10.6.1. We did not have data regarding percentage of preferred food for each point of the grid as we only had data from the farms affected. With these data, and using the model averaging selection, we predicted the damage intensity for each point of the grid and created vulnerability maps for different scenarios: (A-C) a different proportion of highly preferred crops by elephants in all the farms (0, 50 and 100 % of preferred crops), (D) a scenario of reduction in water availability (as expected output for climate change) with 50 % of preferred crops. Reduction of water availability was performed by removing all the small seasonal streams and waterbodies, since these sources are expected to disappear due to climate change (Haile et al., 2020). The maps generated only represent the damage intensity in case elephants reach the farm. We chose to predict for those four scenarios as they are the most immediate changes that can or are already happening. Scenarios A-C only depend on the Government's and farmers' willingness to change to non-palatable crops according to Montero-Botey et al. (2022) findings. On the other hand, scenario D is already happening during intense drought years which are expected to be more frequent in the future.

### 2.3.6. *Probability of farm damage based on distance to waterbodies*

As elephants are water dependent, we also explored how the distance to waterbodies influences the probability of a farm being damaged. To do so, we fitted a binomial (1/0) Generalized Linear Model (GLM) with the same grid of points ($100 \times 100$ m). The points of the grid inside a 100 m radius buffer area of any farm affected (data of the enumerators) were considered as affected (1), and those outside the buffer were considered as not affected (0). For each point, we calculated the distance to the nearest waterbody. With this variable we created the binomial GLM and a combined graph (histogram plus logistic curve) for the representation of the results, following the recommendations of Smart et al. (2004). To create the graphs we used the 'plot.logi.hist' function from the 'pobbio' library of R.

## 3. Results

### 3.1. *Crop preference by elephants*

Crops were grouped into three categories according to their selection index by elephants across the 32 crop types (Appendix S2).

Pineapple, pumpkin, watermelon, tomato, papaya and bananas were the most preferred crops ($w_i \geq 3$; Appendix S2); however pineapple, tomatoes and watermelon were found in a few farms (<10). Maize was a highly preferred crop (selection ratio of 1.46) and the most cultivated in the area.

### 3.2. *Damaged farms and elephant presence*

In terms of elephant damage, there was a total of 904 farms affected for the five study villages (180.8 ± 50.80 farms per village), with a total of 212 days of elephant presence in the area (80 days of elephant presence in more than one village at the same time) and an average of 69.2 ± 17.12 days of elephant presence per village (range 20–121 days) between August 2019 and August 2020 (Table 1). Kajima, Rahaleo and Nambecha had elephants throughout the year with a peak between February and April (Rahaleo also had a peak in December) and a minimum in October, meanwhile Mpanji and Msiaje had elephants only from January to August. The average intensity of damage (proportion of area damaged in a farm as a percentage) in all the farms visited by the enumerators was 37.92 % ± 1.16 (39.09 % ± 3.66 per village), with a proportion of highly preferred crops of 58.84 % ± 1.31 per farm (54.96 % ± 7.71 per village). Rahaleo village was by far the most affected village (number of incidents with people, days of elephant visits and number of farms affected) followed by Nambecha, Kajima, Msiaje and Mpanji (Table 1). However, damage intensity was higher in Mpanji (Table 1). The number of elephants reported involved in the incidents varied between 1 and 68 (15.27 ± 14.02, median =10).

### 3.3. *Land use change*

Overall, in our study area, the percentage of farmland increased on average by 437.61 % ± 43.75 (range 334–524 %) per village from 1990 and 2017 (Table 1). The total forest cover loss (closed and open) in the study area was 35.45 % (40.47 % ± 6.87 per village). Closed forests rather than open forests, showed the greatest loss, with 87.98 % reduction in cover (90.5 % ± 5.08 per village). Moreover, waterbodies suffered a dramatical decrease between 1990 and 2017, from around 99.9 % reduction in Msiaje and Kajima to 90.4 % and 54.0 % in Rahaleo and Mpanji, respectively (Table 1). A graphic overview of the land use change in the study area between 1990 and 2017 is found in Appendix S3.

### 3.4. *Factors affecting intensity of crop damage*

The average model (Table 2) showed that the intensity of damage caused by elephants in each farm increased with the proportion of preferred crops (Fig. 2a), and the proportion of elephant shelter in 1990 (Fig. 2b). This latter effect was particularly noticeable when cover for elephant shelter varied between 0 % and 50 % (Fig. 2b). Conversely, the intensity of damage per farm decreased when the human activity (current proportion of settlements and farmland) increased (Fig. 2c). On the other hand, the intensity increased until the proportion of open forest surrounding the farm reached 20 % (for 1 km$^2$ buffer area) and then decreased afterwards (Fig. 2d).

**Table 1**

Summary of land use cover, number of farms affected by elephants between August 2019 and August 2020 and land use changes in each village over the period 1990–2017.

| | Rahaleo | Kajima | Nambecha | Mpanji | Msiaje |
|---|---|---|---|---|---|
| Elephant crop damage | | | | | |
| People/ households affected | 249 | 147 | 149 | 41 | 136 |
| Farms affected | 361 | 166 | 181 | 47 | 149 |
| Days of elephant damage per year | 121 | 85 | 73 | 20 | 47 |
| Crop area damaged (acres) | 220.0 | 110.2 | 151.4 | 108.1 | 198.8 |
| Total area in damaged farms (acres) | 633.3 | 372.1 | 714.6 | 223.0 | 646.3 |
| Average total area of the affected farms (acres) | 2.07 | 2.4 | 4.01 | 3.62 | 4.4 |
| Average proportion of damage in a farm (%) | 40.11 | 38.78 | 31.11 | 52.11 | 33.33 |
| Number of farms with complete crop damaged data* | 306 | 155 | 178 | 47 | 147 |
| Number of farms with all complete data (including GPS location and crop damage) | 252 | 148 | 164 | 47 | 143 |
| Land use and land use change | | | | | |
| Village area (km$^2$) | 614.89 | 337.87 | 187.36 | 45.63 | 205.92 |
| Open forest cover in 1990 (%) | 48.6 | 41.7 | Not available | 19.9 | 27.2 |
| Open forest cover in 2017 (%) | 40.7 | 21.5 | Not available | 35.7 | 20.2 |
| Proportion of open forest cover lost (%) | 16.3 | 48.4 | Not available | -79.3 | 25.9 |
| Cover of closed forest in 1990 (%) | 6.2 | 7.4 | Not available | 37.7 | 11.7 |
| Cover of closed forest in 2017 (%) | 1.5 | 0.5 | Not available | 0.5 | 0.6 |
| Proportion of closed forest loss (%) | 75.71 | 92.8 | Not available | 98.7 | 94.78 |
| Proportion of total forest lost (open +closed forest) (%) | 23 | 55.2 | Not available | 37.2 | 46.5 |
| Farm cover in 1990 (%) | 1.3 | 4.4 | Not available | 2.0 | 2.7 |
| Farm cover in 2017 (%) | 6.4 | 18.9 | Not available | 12.2 | 16.0 |
| Proportion of farmland increase (%) | 397.9 | 334.2 | Not available | 524.36 | 493.98 |
| Waterbodies 1990* (%) | 0.50 | 3.00 | Not available | 0.04 | 0.81 |
| Waterbodies 2017* (%) | 0.05 | <0.001 | Not available | 0.02 | <0.001 |
| Proportion of waterbodies lost* (%) | 90.4 | 99.9 | Not available | 54.0 | 99.9 |

*Referring to both permanent and seasonal waterbodies

Finally, we found that intensity of damage decreased with distance to water (Fig. 2e) but increased with greater proportion of closed woodland (Fig. 2f). However, both distance to water and proportion of closed forest showed lower importance in the model (Table 2).

### 3.5. *Predictions of crop damage intensity under different scenarios*

Models predicting elephant damage intensity in each farm for the four scenarios: Scenario A-C: 0 %, 50 %, 100 % of preferred crops cultivated in each farm, respectively, and Scenario D, -with reduction in water availability- are shown in Fig. 3a-d, respectively (data only for Kajima village as an example). For the rest of the villages, maps of predicted damage for the four scenarios are shown in Appendix S4 (Rahaleo) and Appendix S5 (Msiaje and Mpanji). These maps reveal a significant increase in the elephant damage for scenarios B, C and D, with an average elephant damage of 53.58 % ± 19.15, 63.45 % ± 18.79 and 49.7 % ± 14.64 for scenarios B, C, D, respectively, while scenario A presents an average elephant damage of 17.03 % + 13.74 (Fig. 3).

### 3.6. *Probability of farm damage based on distance to waterbodies*

Results from the binomial GLM show that the probability of a farm being damaged by elephants decreases with distance to waterbodies (Appendix S6; Appendix S7). Thus, most farms affected by elephants (65 %) were at < 250 m from the nearest waterbody (28.5 % in the first 60 m from the river). The probability of farm damage significantly decreased from 250 to 800 m to waterbodies and was negligible after 800 m (Appendix S7). The predicted intensity of damage in different scenarios for farms located < 800 m from waterbodies (60.2 % of the total farmland), highlighting those < 250 m from the water bodies (22.9 % of the total farmland) are given in Fig. 4. In scenario D (Fig. 4d), there was a 45.8 % decrease in the predicted area damaged by elephants within 800 m from water bodies.

## 4. Discussion

Our results show that elephant incidents were frequent in the study area between August 2019 and August 2020, affecting numerous households. The mean damage intensity per farm was almost 38 %, which is higher than that reported in other studies (Graham et al., 2010; Tiller et al., 2021). This damage not only produces a high financial and opportunity cost (Hill, 2004) but also puts the food security of farmers and their families at risk (Drake et al., 2021) and, eventually, their health (Rubin, 2015). In addition, the frequent presence of elephants in the villages (mean of 69 days per year) increases the chances of incidents with elephants and creates a feeling of insecurity, which usually restrict the movement of people (Mayberry et al., 2017) and can even affect the access to education for kids (Haule et al., 2002, Sitati et al., 2005). Moreover, the long distance between villages and the limited resources represent a challenge for the Wildlife Division and rangers to address human-elephant incidents on time (Urio, 2020). Consequently, the negative consequences of coexisting with elephants, the delay on the Wildlife Division response and the limited incentives for conservation, are creating a growing animosity against elephants and conservation initiatives in the local communities of the Selous-Niassa Wildlife corridor (Zafra-Calvo et al.,2018). Therefore, in the near future, it would be crucial to implement viable and context-specific mitigation strategies to reduce human-elephant coexistence challenges in order to ensure long-term elephant conservation and the maintenance of the corridor protection. In this context, conflict prediction can play an important role on the design of land use plans and mitigation strategies (Hahn et al., 2023).

Our results showed that the intensity of elephant damage was mainly related to elephant crop preferences and the present and past (~30 years prior) abundance of elephant shelter (forest) surrounding the farm. In contrast, there was a negative relationship of elephant crop damage with the current proportion of farmland and settlements surrounding the farm and the distance to water.

The effect of the abundance of preferred food on elephant crop damage in a particular farm is in line with previous studies (Malugu et al., 2011; Montero-Botey et al., 2021). Interestingly, our predictions show an increase of more than 35 % of farmland damaged by elephants when comparing the scenario with no preferred crops with that of 50 % of farmland covered by preferred crops (Scenarios A and B). However, the increase of damage intensity due to a change from 50 % to 100 % of preferred crops (Scenarios B and C) is only 10 %, which indicates a non-linear relationship with sharper effect at low-moderate levels (<50 % preferred crops). Therefore, promoting cultivation of non-palatable crops, particularly in areas frequently visited by elephants, may strongly reduce the impact of elephants in the farms, and it has been proven feasible when there is participation of local communities and managers as well as political willingness (Dewalt, 1993; Negash and Swinnen, 2013). However, such change might be challenging for local communities as they may become more dependent on external sources to access traditional basic food such as maize flour (Baiphethi et al., 2009).

**Table 2**
Summary of the average beta-regression model conducted to analyse variables affecting the intensity of elephant damage in farms (n = 590).

| Fixed effects | Relative importance | Averaged estimate | Standard error | z-value | p-value |
|---|---|---|---|---|---|
| Proportion of farms/settlements (%) | 1.00 | -0.27605 | 0.08059 | 3.425 | 0.000614 *** |
| Proportion of preferred crops in the farm (%) | 1.00 | 0.19934 | 0.05980 | 3.334 | 0.000857 *** |
| Proportion of open woodland (%) | 0.86 | -0.19127 | 0.08388 | 2.280 | 0.022588 * |
| Proportion of shelter (%) in 1990 in 1 $km^2$ buffer circle | 0.81 | 0.16831 | 0.07472 | 2.253 | 0.024288 * |
| Proportion of closed woodland (%) in 1 $km^2$ | 0.47 | 0.08163 | 0.06061 | 1.347 | 0.178024 |
| Distance to water bodies (m) | 0.47 | -0.08016 | 0.06382 | 1.256 | 0.209124 |

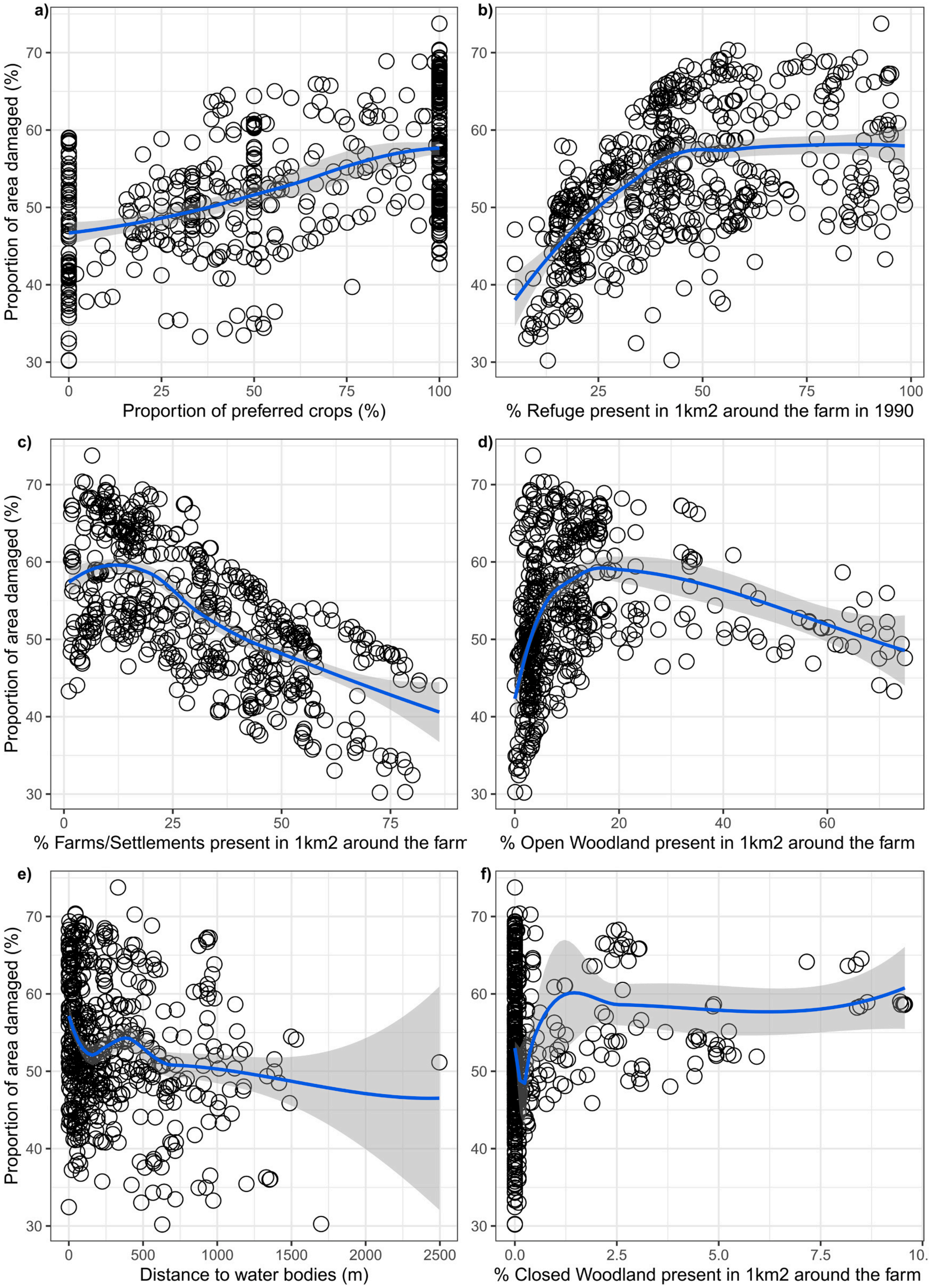


**Fig. 2.** Fitted averaged model curves showing the influence of land use and water availability on elephant damage intensity (proportion of area damaged as %). Area in grey shows 95 % confidence interval.

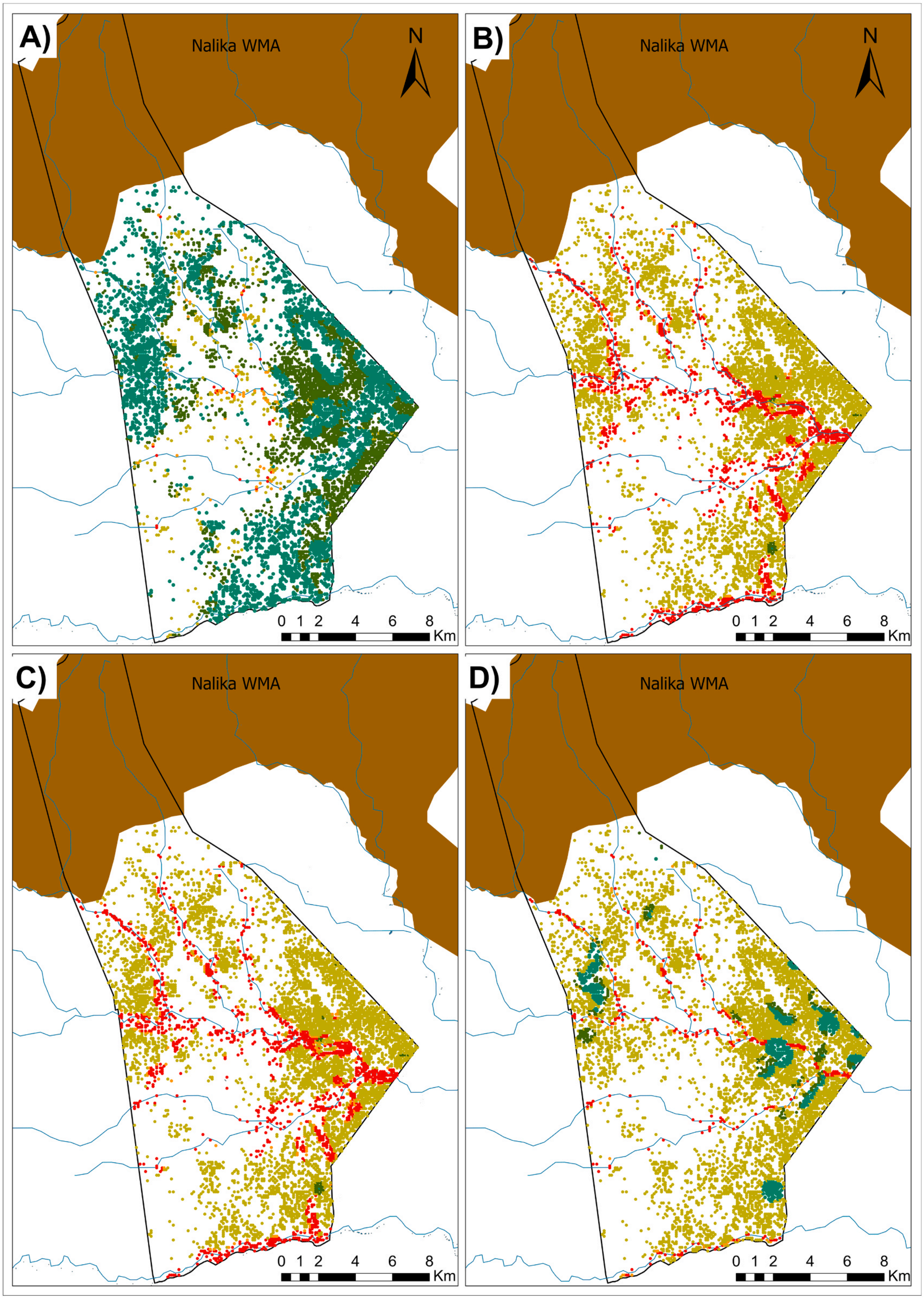
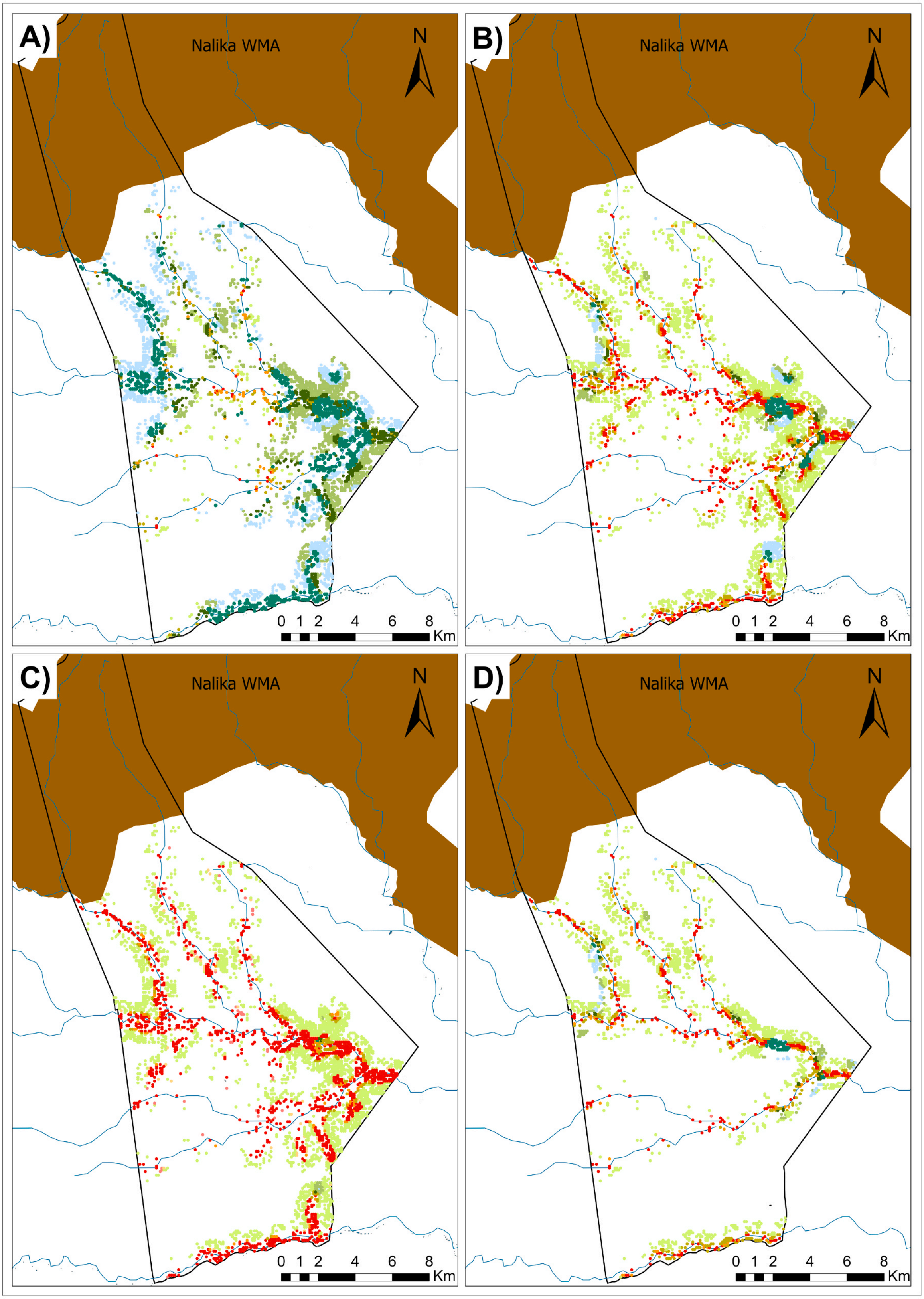


**Fig. 3.** Predicted elephant damage intensity (% of farm area affected) in Kajima village for the different scenarios A-D: A) 0 % of preferred crops cultivated in each farm; B) 50 % of preferred crops cultivated in each farm; C) 100 % of preferred crops cultivated in each farm; D) 50 % of preferred crops cultivated in each farm and water reduction scenario (no water available in small seasonal streams). Different coloured dots indicate different percentages of predicted damage in each farm. Blue (0–20 %), Deep green (20–40 %), Khaki green (40–60 %), Orange (60–80 %), Red (80–100 %).



*(caption on next page)*

**Fig. 4.** Predicted damage intensity with distance to water in farms of Kajima village (within 800 m from water sources) in four different scenarios A-D: A) 0 % of preferred crops cultivated in each farm B) 50 % of preferred crops cultivated in each farm C) 100 % of preferred crops cultivated in each farm D) 50 % of preferred crops cultivated in each farm and water reduction scenario (no water available in small seasonal streams).The coloured dots indicate different percentages of predicted damages in each farm; Blue (0–20 %), Deep green (20–40 %), Khaki green (40–60 %), Orange (60–80 %), Red (80–100 %). Light colours depict farms located between 250 and 800 m from water sources. Bright colours depict farms near (< 250 m) the water sources.

Furthermore, comparing our results of elephant crop selection with those from Montero-Botey et al. (2021) in the same study area, we can affirm that elephants maintain their preferences over time. The results of our study are based on a larger sample size and a greater array of crop types, which provide valuable information on elephant crop preferences, given the exhaustive analyses on 32 crop types (Appendix S2) that are widely distributed in many areas of Africa.

The importance of the abundance of preferred crops agrees with numerous studies reporting seasonality on elephant crop damage as they prefer mature crops (Chiyo et al., 2005; Gubbi, 2012; Chen et al., 2016). This explains the peak of elephant incidents between February and April in the study area as it matches with maturation season of several crops (e.g. short cycle maize and pumpkin, or the December peak in Rahaleo that matches with mango fruiting season). However, our results, especially in the northern part of the study area report that only one third of the days are free of elephant encounters. Furthermore, the low frequency of elephant damage in October could be related to the lack of crops and farmers in the farms at the end of the dry season, which also coincides with the low reporting of elephant presence. These results are in line with Tiller et al. (2021) who reported elephant crop damage incidents in the Trans Mara region all year around. Tiller et al. (2021) suggest that the continuous presence of elephants in the farmland might be related to livestock, human settlement and farmland increase.

Interestingly, we found that in the last 30 years there has been a considerable deforestation and vast increase of farmland in the study area with a dramatic loss in closed forest cover and waterbodies, and a moderate-high reduction in open forest. These changes represent a threat to elephants (Martínez-Freiría et al., 2016; Boult et al., 2019) by reducing and fragmenting their habitats and historic ranges (Ripple et al., 2015) and reducing water availability (Boult et al., 2019). In addition, these land use changes favour the intersection of human and elephant activities and the competition for resources (Hoare, 1999), which may lead to increasing negative interactions between humans and elephants (Montero-Botey et al., 2022).

In fact, elephants in Selous ecosystem have historically shown open to dense woodland as their preferred habitat (Matzke, 1971). Therefore, and in line with our results we could expect greater abundance of elephants in forested areas, and therefore a positive relationship between historical presence of forest in 1990 around the farm, and crop damage intensity in that farm. If a farm is established in an area that used to be part of an elephant herd home range (forest), it could be expected to be more frequently visited than other farms in areas rarely visited in the past (for example grassland). In fact, previous studies have shown that herds might be influenced by site fidelity and natal philopatry (Pinter-Wollman, 2009; Loarie et al., 2009) which influences matriarch movement decisions during her long lifespan (maximum 74 years; Lee et al., 2012). These findings are particularly concerning as there have been numerous reports of elephants giving birth near farms along the Selous-Niassa Wildlife Corridor (pers. obs.), which could initiate a new generation of elephants that acclimate to live around farms. To reduce damage intensity in the future, it would be desirable to implement proper land use plans. For example, by suppressing or reducing deforestation of adequate and historical areas for elephants. Alternatively, farmers may consider moving away their farms from elephant core home areas. This change in farm location might be challenging but it has been already implemented in Rahaleo village (in 2022), reducing human-elephant conflicts drastically (unpublished data). In addition, the current proximity of forest patches might facilitate elephants to find shelter in case of being discovered and chased away from the farms, sometimes used as staging posts for farm incursions (Tiller et al., 2021; Hahn et al., 2023). This may explain why elephant damage intensity rises when the current proportion of forest around the farm increases up to 20 %. However, when forest cover is greater than 20 %, the damage intensity decreases possibly because there is an increase of food availability in forests reducing the need for elephants to enter farms in search of food (Amaya et al., 2021) and therefore less probability of elephants wandering in human-dominated areas (Chen et al., 2016). Crop damage intensity in a farm was negatively associated with the proportion of farmland and settlements surrounding the farm. Elephants are conscious of the risk they take when entering a farm due to human presence (Ahlering et al., 2011). Generally, greater proportion of farms and settlements surrounding a particular farm indicates higher human population density and higher probability of encountering humans, therefore, elephants minimize the time spent in populated farms (Douglas-Hamilton et al., 2005; Graham et al., 2009; Songhurst et al., 2016). For the same reason, it is more likely that elephants are chased away sooner by farmers in areas with higher human presence compared to isolated and remote farms (Sitati et al., 2005).

Finally, the negative association of both intensity and probability of damage with distance to water agrees with previous literature (Ben-Shahar, 1993; Smith and Kasiki, 2000; Montero-Botey et al., 2021). This is due to the strong water dependency of elephants causing large-scale damages when elephants gather in family groups (Stokke & du Toit, 2002). Our results suggest that farming further away from rivers (or permanent waterbodies) might be a plausible strategy to reduce elephant crop damage. The law in Tanzania, in particular The Water Resources Management Act article 6.34 (MWT, 2009) prohibits human activities within 60 m from a water source, dam or reservoir. However, this law, as in many other areas of Tanzania (Arduino et al., 2012; Kironde, 2016; Mkude et al., 2018) is not being followed or enforced in the corridor, which might have played an important role in the drastic reduction of waterbodies in the area over the last 30 years (Table 1). Awareness and enforcement of this law could reduce crop damages by elephants and help protect the scarce and dwindling water resources. However, the majority of the farms in the study area are in the first 500–700 m from waterbodies and cultivating further than 60–250 m from the waterbodies is not suitable for many types of crops.

Therefore, enforcing the law might create social conflicts for land tenure and social animosity in the local communities as it obliges them to change their traditional way of living (Montero-Botey et al., 2022) and increase the effort of water collection. Alternatively, reducing the area covered by water-demanding crops (such as rice, sugarcane, maize, etc.-Steduto et al., 2012) would strongly diminish the use and demand of the water and may provide a suitable solution for both human-elephant coexistence and climate change challenges.

The water reduction scenario based on the probable disappearance of seasonal secondary water streams in the future provides crucial information for future spatial planification. However, and importantly, the collateral effects of drought on other anthropic and ecological aspects (e.g., human movements, animal concentration, forest cover, etc.) may add some uncertainty to the expected results shown by our models. Thus, a drought scenario will have not only a significant negative impact on farmers livelihoods, food security and nutrition (Assoumana et al., 2016; Haile et al., 2019) but it will also reduce growing seasons, area suitable for agriculture, access to water and the quality of the water resources (Niang et al., 2014; Sutcliffe et al., 2016). As a result, local communities will probably concentrate around the remaining waterbodies and the competition for water between humans, livestock and wildlife might strongly increase (Ogutu et al., 2008; Ogutu et al., 2014; Bartzke et al., 2018). Therefore, in order to reduce the impact of climate change and competition with wildlife in the long term and increase the resilience of local communities, conservation and government strategies should consider encouraging diversification to non-farming income sources, planting short-season crops, increasing education level and improve the access to credit facilities (Obayelu et al., 2014; Temesgen et al., 2014; Sutcliffe et al., 2016; Fagariba et al., 2018).

Conflict prediction, especially considering the effect of climate change have shown many benefits for wildlife conservation and local communities living near protected areas (Shaffer et al., 2019; Bautista et al., 2021). Although it is possible that not all the elephant related incidents were reported by the enumerators, our large dataset across different villages provided enough confidence and reliability. The method used in this study based on crop monitoring by local scouts (VGS), combined with 30x30m detailed land use maps, proved to be useful to better understand conflict patterns and guide context-specific conflict mitigation strategies. Therefore, we believe the application of this approach would be useful to the study and management of human–wildlife conflict in other sites across the world.

Although our results show the expected intensity of damage in a farm once the elephants have entered, we do not have complete information on elephant movements, which could affect the predicted probability of damage across space. Therefore, to create appropriate land use planning in the future, it would be desirable to complement our results with information on elephant movement, such as collared elephant data.

## 5. Conclusions

This study provides important insights into variables that influence elephant damage in the farms such as land use, water availability and crop types. It also allows predicting, and mapping expected elephant damage for each farm, not only for the study villages but for all the villages surrounding Nyerere National Park and other protected areas with similar ecosystems and elephant crop-raiding patterns. Predictive damage intensity maps are valuable tools for the planification and implementation of mitigation strategies as they give spatial information to identify risk areas, understand the reasons behind that risk and propose suitable solutions.

## Funding

This work was supported by WWF Tanzania (Pachyderm fund) and Universidad Politécnica de Madrid-Funded Research, Development and Innovation Programme (specifically the Funding for predoctoral contracts for the completion of doctoral degrees at UPM schools, faculties, and R&D centers). This research was partly supported by the Grant Reference TED2021–129923B-I00 funded by MCIN/AEI/10.13039/501100011033 and, by the “European Union Next Generation EU/PRTR”.

## CRediT authorship contribution statement

**María Montero Botey**: Investigation, Conceptualization, Methodology, Formal analysis, Writing original draft. **Emanuel Kivuyo:** Data collection, Investigation, Review of final draft. **Noah Sitati:** Review of final draft. **Ramón Perea:** Methodology, Writing-review and editing, Supervision.

## Declaration of Competing Interest

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

## Data availability

Data will be made available on request.

## Acknowledgements

We would like to thank TAWIRI (Tanzanian Wildlife Research Institute) and the Tanzanian Commission for Science and Technology

(COSTECH) for granting permission for the implementation of the study. We also thank the village game scouts that collected the data (Said Halifa Amigo, Mboka Hussen Mbwana, Zuberi Said Msosa and Sephu Ndomondo), the Universidad Politécnica de Madrid-Funded Research, Development and Innovation Programme, WWF Tanzania for financial support to VGS during data collection and FZS for sharing their land use maps.

### *Article impact statement*

Elephant conservation strategies should consider crop palatability and land use conversion by using predictive elephant damage maps.

### *Supporting information*

Additional supporting information may be found in the online version of the article at the publisher's website.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2024.e03068.

## References

Ahlering, M.A., Millspaugh, J.J., Woods, R.J., Western, D., Eggert, L.S., 2011. Elevated levels of stress hormones in crop-raiding male elephants. Anim. Conserv. 14 (2), 124–130.

Amaya, P.C., Nourtier, M., Montfort, F., Fusari, A., Randrianary, T., Richard, E., Prin, T., Valls-Fox, H., 2021. Are elephants attracted by deforested areas in miombo woodlands? Afr. J. Ecol. 59 (3), 742–748.

Arduino, S., Colombo, G., Ocampo, O.M., Panzeri, L., 2012. Contamination of community potable water from land grabbing: a case study from rural Tanzania. Water Altern. 5 (2), 344–359.

Assoumana, B.T., Ndiaye, M., Puije, G.V.D., Diourte, M., Gaiser, T., 2016. Comparative assessment of local farmers' perceptions of meteorological events and adaptations strategies: two case studies in Niger Republic. J. *Sustain. Dev.* 9, 118–135.

Ayeni, A.O., Aborisade, A.G., Onuminya, T.O., Soneye, A.S.O., Ogundipe, O.T., 2023. Urban development in Africa and impact on biodiversity. Curr. Landsc. Ecol. Rep. 8 (2), 73–89.

Baiphethi, M.N., Jacobs, P.T., 2009. The contribution of subsistence farming to food security in South Africa. Agrekon 48, 459–482.

Baldus, R.D., Hahn, R., 2009. The Selous–Niassa Wildlife Corridor in Tanzania: Biodiversity Conservation from the Grassroots. Practical Experiences and Lessons from Integrating Local Communities into Trans-boundary Natural Resources Management. FAO & CIC, Budapest, Hungary.

Barton, K. (2023). MuMIn: Multi-Model Inference. R package version 1.47.5 ⟨https://cran.r-project.org/web/packages/MuMIn/index.html⟩.

Bartzke, G.S., Ogutu, J.O., Mukhopadhyay, S., Mtui, D., Dublin, H.T., Piepho, H.P., 2018. Rainfall trends and variation in the Maasai Mara ecosystem and their implications for animal population and biodiversity dynamics. PloS One 13 (9), e0202814.

Bautista, C., Revilla, E., Berezowska-Cnota, T., Fernández, N., Naves, J., Selva, N., 2021. Spatial ecology of conflicts: unravelling patterns of wildlife damage at multiple scales. Proc. R. Soc. B 288 (1958), 20211394.

Bennett, E.L., 2015. Legal ivory trade in a corrupt world and its impact on African elephant populations. Conserv. Biol. 29 (1), 54–60.

Ben-Shahar, R., 1993. Patterns of elephant damage to vegetation in northern Botswana. Biol. Conserv. 65 (3), 249–256.

Bluwstein, J., Lund, J.F., 2018. Territoriality by conservation in the Selous-Niassa Corridor in Tanzania. World Dev. 101, 453–465.

Bohrer, G., Beck, P.S., Ngene, S.M., Skidmore, A.K., Douglas-Hamilton, I., 2014. Elephant movement closely tracks precipitation-driven vegetation dynamics in a Kenyan forest-savanna landscape. Mov. Ecol. 2 (1), 1–12.

Boult, V.L., Fishlock, V., Quaife, T., Hawkins, E., Moss, C., Lee, P.C., Sibly, R.M., 2019. Human-driven habitat conversion is a more immediate threat to Amboseli elephants than climate change. Conserv. Sci. Pract. 1 (9), e87.

Boult, V.L., Quaife, T., Fishlock, V., Moss, C.J., Lee, P.C., Sibly, R.M., 2018. Individual-based modelling of elephant population dynamics using remote sensing to estimate food availability. Ecol. Model. 387, 187–195.

Charnley, S., Frey, G., Makala, J., 2022. Community forests, timber production, and certification: success factors in the African context. Ecol. Soc. 27 (3), 6.

Chase, M.J., Schlossberg, S., Griffin, C.R., Bouché, P.J., Djene, S.W., Elkan, P.W., Ferreira, S., Grossman, F., Kohi, E.M., Landen, K., Omondi, P., Peltier, A., Selier, S.A. J., Sutcliffe, R., 2016. Continent-wide survey reveals massive decline in African savannah elephants. PeerJ 4, e2354.

Chen, Y., Marino, J., Chen, Y., Tao, Q., Sullivan, C.D., Shi, K., Macdonald, D.W., 2016. Predicting hotspots of human-elephant conflict to inform mitigation strategies in Xishuangbanna, Southwest China. PloS One 11 (9), e0162035.

Chiyo, P.I., Cochrane, E.P., Naughton, L., Basuta, G.I., 2005. Temporal patterns of crop raiding by elephants: a response to changes in forage quality or crop availability? Afr. J. Ecol. 43 (1), 48–55.

Chiyo, P.I., Lee, P.C., Moss, C.J., Archie, E.A., Hollister-Smith, J.A., Alberts, S.C., 2011. No risk, no gain: effects of crop raiding and genetic diversity on body size in male elephants. Behav. Ecol. 22 (3), 552–558.

Chiyo, P.I., Moss, C.J., Alberts, S.C., 2012. The influence of life history milestones and association networks on crop-raiding behavior in male African elephants. PLoS One 7 (2), e31382.

Cribari-Neto, F., Zeileis, A., 2010. Beta regression in R. J. Stat. Softw. 34, 1–24.

Dai, A., 2011. Drought under global warming: a review. Wiley Interdiscip. Rev.: Clim. Change 2 (1), 45–65.

Dewalt, K.M., 1993. Nutrition and the commercialization of agriculture: ten years later. Soc. *Sci. Med.* 36 (11), 1407–1416.

Dickman, A.J., 2010. Complexities of conflict: the importance of considering social factors for effectively resolving human-wildlife conflict. Anim. Conserv. 13, 458–466.

Douglas-Hamilton, I., 1987. African elephants: population trends and their causes. Oryx 21 (1), 11–24.

Douglas-Hamilton, I., Krink, T., Vollrath, F., 2005. Movements and corridors of African elephants in relation to protected areas. Naturwissenschaften 92 (4), 158–163.

Drake, M.D., Salerno, J., Langendorf, R.E., Cassidy, L., Gaughan, A.E., Stevens, F.R., Pricope, N.G., Hartter, J., 2021. Costs of elephant crop depredation exceed the benefits of trophy hunting in a community-based conservation area of Namibia. Conserv. Sci. Pract. 3 (1), e345.

Druce, H.C., Pretorius, K., Slotow, R., 2008. The response of an elephant population to conservation area expansion: Phinda Private Game Reserve, South Africa. Biol. Conserv. 141 (12), 3127–3138.

Fagariba, C.J., Song, S., Baoro, S.K.G.S., 2018. Climate change in Upper East Region of Ghana; challenges existing in farming practices and new mitigation policies. Open Agric. 3 (1), 524–536.

Fisher, M., 2016. Whose conflict is it anyway? Mobilizing research to save lives. Oryx 50 (3), 377–378.

Freckleton, R.P., 2011. Dealing with collinearity in behavioural and ecological data: model averaging and the problems of measurement error. Behav. Ecol. Sociobiol. 65 (1), 91–101.

Goldenberg, S.Z., Douglas-Hamilton, I., Wittemyer, G., 2016. Vertical transmission of social roles drives resilience to poaching in elephant networks. Curr. Biol. 26 (1), 75–79.

Goswami, V.R., Vasudev, D., 2017. Triage of conservation needs: the juxtaposition of conflict mitigation and connectivity considerations in heterogeneous, human-dominated landscapes. Front. Ecol. Evol. 4, 144.

Graham, M.D., Douglas-Hamilton, I., Adams, W.M., Lee, P.C., 2009. The movement of African elephants in a human-dominated land-use mosaic. Anim. Conserv. 12 (5), 445–455.

Graham, M.D., Notter, B., Adams, W.M., Lee, P.C., Ochieng, T.N., 2010. Patterns of crop-raiding by elephants, Loxodonta africana, in Laikipia, Kenya, and the management of human–elephant conflict. Syst. Biodivers. 8 (4), 435–445.

Graham, M., Ochieng, T., 2008. Uptake and performance of farm-based measures for reducing crop raiding by elephants Loxodonta africana among smallholder farms in Laikipia District. Kenya *Oryx* 42 (1), 76–82.

Grueber, C.E., Nakagawa, S., Laws, R.J., Jamieson, I.G., 2011. Multimodel inference in ecology and evolution: challenges and solutions. J. Evolut. Biol. 24 (4), 699–711.

Gubbi, S., 2012. Patterns and correlates of human–elephant conflict around a south Indian reserve. Biol. Conserv. 148 (1), 88–95.

Guerbois, C., Chapanda, E., Fritz, H., 2012. Combining multi-scale socio-ecological approaches to understand the susceptibility of subsistence farmers to elephant crop raiding on the edge of a protected area. J. Appl. Ecol. 49 (5), 1149–1158.

Hahn, N.R., Wall, J., Denninger-Snyder, K., Sairowua, W., Goss, M., Ndambuki, S., Eblate, E., Mbise, N., Kiambi, S., Wittemyer, G., 2023. Staging behaviours identify spatial and temporal risk of human-wildlife conflict. J. Appl. Ecol. 60 (7), 1495–1506.

Haile, G.G., Tang, Q., Hosseini-Moghari, S.M., Liu, X., Gebremicael, T.G., Leng, G., Kebede, A., Xu, X., Yun, X., 2020. Projected impacts of climate change on drought patterns over East Africa. Earth'S. Future 8 (7) e2020EF001502.

Haile, G.G., Tang, Q., Sun, S., Huang, Z., Zhang, X., Liu, X., 2019. Droughts in East Africa: causes, impacts and resilience. Earth-Sci. Rev. 193, 146–161.

Harris, G.M., Russell, G.J., Van Aarde, R.I., Pimm, S.L., 2008. Rules of habitat use by elephants Loxodonta africana in southern Africa: insights for regional management. Oryx 42 (1), 66–75.

Haule, K.S., Johnsen, F.H., Maganga, S.L.S., 2002. Striving for sustainable wildlife management: the case of Kilombero Game Controlled Area, Tanzania. J. Environ. Manag. 66 (1), 31–42.

Haynes, G., 2012. Elephants (and extinct relatives) as earth-movers and ecosystem engineers. Geomorphology 157, 99–107.

Hill, C.M., 2004. Farmers' perspectives of conflict at the wildlife– agriculture boundary. Hum. Dimens. Wildl. 9, 279–286.

Hoare, R.E., 1999. Determinants of human-elephant conflict in a land-use mosaic. J. Appl. Ecol. 36 (5), 689–700.

Ihwagi, F.W., Thouless, C., Wang, T., Skidmore, A.K., Omondi, P., Douglas-Hamilton, I., 2018. Night-day speed ratio of elephants as indicator of poaching levels. Ecol. Indic. 84, 38–44.

Jew, E.K., Dougill, A.J., Sallu, S.M., 2017. Tobacco cultivation as a driver of land use change and degradation in the miombo woodlands of south-west Tanzania. Land Degrad. Dev. 28 (8), 2636–2645.

Kaba, A.J., 2020. Explaining Africa's rapid population growth, 1950 to 2020: Trends, factors, implications, and recommendations. Sociol. mind 10 (4), 226–268.

Karidozo, M., Osborn, F.V., 2015. Community based conflict mitigation trials: Results of field test of chilli as an elephant deterrent. J. Biodivers. Endanger. Species 3, 144.

Kinahan, A.A., Stuart, L., Pimm, S.L., Rudi, J., 2007. Ambient temperature as a determinant of landscape use in the savanna elephant. *Loxodonta africana*. J. Therm. Biol. 32 (1), 47–58.

King, L.E., Lawrence, A., Douglas-Hamilton, I., Vollrath, F., 2009. Beehive fence deters crop-raiding elephants. Afr. J. Ecol. 47 (2), 131–137.

Kioko, J., Muruthi, P., Omondi, P., Chiyo, P.I., 2008. The performance of electric fences as elephant barriers in Amboselli, Kenya. South Afr. J. Wildl. Res. 38, 52–58.

Kironde, J.M.L., 2016. Governance deficits in dealing with the plight of dwellers of hazardous land: the case of the Msimbazi River Valley in Dar es Salaam, Tanzania. Curr. Urban Stud. 4, 303–328.

Lee, P.C., Sayialel, S., Lindsay, W.K., Moss, C.J., 2012. African elephant age determination from teeth: validation from known individuals. Afr. J. Ecol. 50 (1), 9–20.

Linkie, M., Dinata, Y., Nofrianto, A., Leader-Williams, N., 2007. Patterns and perceptions of wildlife crop raiding in and around Kerinci Seblat National Park, Sumatra. Anim. Conserv. 10 (1), 127–135.

Loarie, S.R., Van Aarde, R.J., Pimm, S.L., 2009. Fences and artificial water affect African savannah elephant movement patterns. Biol. Conserv. 142 (12), 3086–3098.

Malugu, L.T., Hoare, R.E., Mpanduji, D.G., & Maganga, S.L.S. (2011, December). Status and mitigation measures of elephant crop raiding in areas adjacent to Grumeti-Ikorongo Game Reserves, Northern Tanzania. In *Proceeding of the eighth TAWIRI Scientific Conference*, pp. 12–22. TAWIRI, Arusha, Tanzania.

Manly, B.F.J., McDonald, L.L., Thomas, D.L., McDonald, T.L., Erickson, W.P., 2002. Resource Selection by Animals: Statistical Analysis and Design for Field Studies. Kluwer, Nordrecht, The Netherlands.

Mariki, S.B., Svarstad, H., Benjaminsen, T.A., 2015. Elephants over the cliff: explaining wildlife killings in Tanzania. Land Use Policy 44, 19–30.

Martínez-Freiría, F., Tarroso, P., Rebelo, H., Brito, J.C., 2016. Contemporary niche contraction affects climate change predictions for elephants and giraffes. Divers. Distrib. 22 (4), 432–444.

Matsika, T.A., Adjetay, J.A., Obopile, M., Songhurst, A.C., McCulloch, G., Stronza, A., 2020. Alternative crops as a mitigation measure for elephant crop raiding in the eastern Okavango Panhandle. Pachyderm 61, 140–152.

Matzke, G.E., 1971. Settl. reorganization Prod. Afr. Wildl. miombo For. Land.: A Spat. Anal. (Dr. Diss., Okla. State Univ. ).

Mayberry, A.L., Hovorka, A.J., Evans, K.E., 2017. Well-being impacts of human-elephant conflict in Khumaga, Botswana: exploring visible and hidden dimensions. Conserv. Soc. 15 (3), 280–291.

MCDI, 2018. MCDI Strategy Sustain. Plan July 2018 – June 2023.

Mkude, I.T., Kodom, K., Onoyinka, A.A., Saria, J., Mihale, M.J., 2018. Spatial and temporal variations of physicochemical parameters in surface water of Wami River, Tanzania. Int. J. Dev. Sustain. 7 (6), 1936–1945.

Montero-Botey, M., Perea, R., 2023. An increasing human-elephant conflict? Impact of African elephant on cultivated cashew trees. Eur. J. Wildl. Res. 69 (1), 5.

Montero-Botey, M., San Miguel, A., Perea, R., 2021. Food preferences determine human–elephant coexistence in African woodlands. Oryx 55 (5), 747–754.

Montero-Botey, M., Soliño, M., Perea, R., Martínez-Jauregui, M., 2022. Let us give voice to local farmers: preferences for farm-based strategies to enhance human-elephant coexistence in Africa. Animals 12 (14), 1867.

Mpanduji, D.G., 2004. Population structure, movement and health status of elephants and other wildlife in the Selous-Niassa Wildlife Corridor. Southern Tanzania (Doctoral dissertation, Freie Universität Berlin).

Mwambene, P.L., Mbwile, R.P., Hoeggel, F.U., Kimbi, E.C., Materu, J., Mwaiganju, A., Madoffe, S., 2014. Assessing dynamics of forced livestock movements, livelihoods and future development options for pastoralists/agro-pastoralists in Ruvuma and Lindi Regions, in Southern Tanzania. Livest. Res. Rural Dev. 26 (1).

MWT, 2009. Ministry of Water of the United Republic of Tanzania (2009). The Water Resources Management Act, 2009. Dar es Salaam.

Naughton-Treves, L., 1998. Predicting patterns of crop damage by wildlife around kibale National Park, Uganda. Conserv. Biol. 12 (1), 156–168.

Negash, M., Swinnen, J.F., 2013. Biofuels and food security: micro-evidence from Ethiopia. Energy Policy 61, 963–976.

Newmark, W.D., Manyanza, D.N., Gamassa, D.G.M., Sariko, H.I., 1994. The conflict between wildlife and local people living adjacent to protected areas in Tanzania: human density as a predictor. Conserv. Biol. 8 (1), 249–255.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., Urquhart, P., 2014. Climate Change 2014: Impacts, Adaptation and Vulnerability. InContribution of Working Group II to the Fifth Assessment Reportof the Inter-Governmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Nyhus, P.J., Tilson, R., 2000. Crop-raiding elephants and conservation implications at Way Kambas National Park, Sumatra, Indonesia. Oryx 34 (4), 262–274.

Obayelu, O.A., Adepoju, A.O., Idowu, T., 2014. Factors influencing farmers' choices of adaptation to climate change in Ekiti State, Nigeria. J. Agric. Environ. Int. Dev. (JAEID) 108 (1), 3–16.

Ogunjobi, J.A., Halidu, S.K., Odebiyi, B.R., Fxentirimam, I.J., 2018. Crop raiding pattern of the African elephant (Loxodonta africana) in farms around Kamuku National Park, Nigeria. Afr. J. Agric. Technol. Environ. *7*, 174–187.

Ogutu, J.O., Piepho, H.P., Dublin, H.T., Bhola, N., Reid, R.S., 2008. El Niño-southern oscillation, rainfall, temperature and normalized difference vegetation index fluctuations in the Mara-Serengeti ecosystem. Afr. J. Ecol. 46 (2), 132–143.

Ogutu, J.O., Piepho, H.P., Said, M.Y., Kifugo, S.C., 2014. Herbivore dynamics and range contraction in Kajiado County Kenya: climate and land use changes, population pressures, governance, policy and human-wildlife conflicts. Open Ecol. J. 7 (1).

Pinter-Wollman, N., 2009. Spatial behaviour of translocated African elephants (Loxodonta africana) in a novel environment: using behaviour to inform conservation actions. Behaviour 146 (9), 1171–1192.

Potapov, P., Turubanova, S., Hansen, M.C., Tyukavina, A., Zalles, V., Khan, A., Song, X.P., Pickens, A., Shen, Q., Cortez, J., 2022. Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nat. Food 3 (1), 19–28.

R Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ⟨http://www.r-project.org/⟩.

Rao, N., Singh, C., Solomon, D., Camfield, L., Sidiki, R., Angula, M., Poonacha, P., Sidibé, A., Lawson, E.T., 2020. Managing risk, changing aspirations and household dynamics: Implications for wellbeing and adaptation in semi-arid Africa and India. World Dev. 125, 104667.

Ripple, W.J., Newsome, T.M., Wolf, C., Dirzo, R., Everatt, K.T., Galetti, M., Hayward, M.W., Kerley, G.I.H., Levi, T., Lindsey, P., Macdonald, D.W., Painter, L.E., Sandom, C.J., Malhi, Y., Terborgh, J., Van Valkenburgh, B., 2015. Collapse of the world's largest herbivores. Sci. Adv. 1 (4), e1400103.

Rode, K.D., Chiyo, P.I., Chapman, C.A., McDowell, L.R., 2006. Nutritional ecology of elephants in Kibale National Park, Uganda, and its relationship with crop-raiding behaviour. J. Trop. Ecol. 22 (4), 441–449.

Rubin, L.P., 2015. Maternal and pediatric health and disease: integrating. Biopsychosocial models and epigenetics. Pediatr. Res. 79, 127–135.

Rweyemamu, M., Kim, J., 2020. Potential environmental hazard to the public from the operation of uranium mining and milling facility. Radiat. Prot. Dosim. 192 (1), 75–88.

Sage, R.F., 2020. Global change biology: a primer. Glob. Change Biol. 26 (1), 3–30.

Seitz, J., & Nyangena, W. (2009). Economic impact of climate change in the East African community (EAC). *Final Report, GTZ Project "Support to the Integration Process in the EAC Region. Arusha*, Tanzania.

Shaffer, L.J., Khadka, K.K., Van Den Hoek, J., Naithani, K.J., 2019. Human-elephant conflict: A review of current management strategies and future directions. Front. Ecol. Evol. 6, 235.

Sitati, N.W., Walpole, M.J., Leader-Williams, N., 2005. Factors affecting susceptibility of farms to crop raiding by African elephants: using a predictive model to mitigate conflict. J. Appl. Ecol. 42 (6), 1175–1182.

Sitati, N.W., Walpole, M.J., Smith, R.J., Leader-Williams, N., 2003. Predicting spatial aspects of human-elephant conflict. J. Appl. Ecol. 40 (4), 667–677.

Smart, J., Sutherland, W.J., Watkinson, A.R., Gill, J.A., 2004. A new means of presenting the results of logistic regression. Bull. Ecol. Soc. Am. 85 (3), 100–102.

Smit, I.P.J., Grant, C.C., Whyte, I.J., 2007. Elephants and water provision: what are the management links? Divers. Distrib. 13 (6), 666–669.

Smit, J., Pozo, R., Cusack, J., Nowak, K., Jones, T., 2019. Using camera traps to study the age-sex structure and behaviour of crop-using elephants in Udzungwa Mountains National Park, Tanzania. Oryx 53 (2), 368–376.

Smith, R.J., & Kasiki, S.M. (2000). A spatial analysis of human–elephant conflict in the Tsavo ecosystem, Kenya. *AfESG Report. IUCN/SSC, Gland, Switzerland*.

Songhurst, A.C., 2012. Competition between people and elephants in the Okavango Delta Panhandle, Botswana. Doctoral dissertation, Imperial College London.

Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., 2012. Crop yield response to water, 1028. FAO, Rome.

Stokke, S., Du Toit, J.T., 2002. Sexual segregation in habitat use by elephants in Chobe National Park, Botswana. Afr. J. Ecol. 40 (4), 360–371.

Sutcliffe, C., Dougill, A.J., Quinn, C.H., 2016. Evidence and perceptions of rainfall change in Malawi: do maize cultivar choices enhance climate change adaptation in sub-Saharan Africa? Reg. Environ. Change 16 (4), 1215–1224.

TAWIRI, 2019. Aerial Wildlife Survey of Large Animals and Human Activities in the Selous-Mikumi Ecosystem, Dry Season 2018. TAWIRI Aerial Survey Report.

TAWIRI, 2024. Aerial Wildlife Survey of Large Animals and Human Activities in the Selous-Mikumi Ecosystem, Dry Season 2022. TAWIRI Aerial Survey Report.

Temesgen, D., Yehualashet, H., Rajan, D.S., 2014. Climate change adaptations of smallholder farmers in South Eastern Ethiopia. J. Agric. Ext. Rural Dev. 6 (11), 354–366.

UNEP-WCMC, 2016. The State of Biodiversity in Africa: A mid-term review of progress towards the Aichi Biodiversity Targets. UNEP-WCMC, Cambridge, UK.

United Republic of Tanzania Central Census Office, 2013. 2022 population and housing census. National Bureau of Statistics (Tanzania).

USGS (UNITED STATES GEOLOGICAL SURVEY) (2019). Tunduru, Ruvuma, Southern Highlands Zone, Tanzania. OLI/TIRS combined Landsat 8, Natural color, Landviewer. eos.com/landviewer [Accessed 30 November 2020].

Vermaat, J.E., Hellmann, F.A., van Teeffelen, A.J., van Minnen, J., Alkemade, R., Billeter, R., Beierkuhnlein, C., Boitani, L., Cabeza, M., Feld, C.K., WallisDeVries, M. F., 2017. Differentiating the effects of climate and land use change on European biodiversity: a scenario analysis. Ambio 46 (3), 277–290.

Vertriest, W., Palke, A.C., Renfro, N.D., 2019. Field Gemology: building a research collection and understanding the development of gem deposits. Gems Gemol. 55 (4), 490–511.

Vogel, S.M., Blumenthal, S.A., de Boer, W.F., Masake, M., Newton, I., Songhurst, A.C., McCulloch, G., Stronza, A., Henley, M.D., Coulson, T., 2020. Timing of dietary switching by savannah elephants in relation to crop consumption. Biol. Conserv. 249, 108703.

Vogel, E., Donat, M.G., Alexander, L.V., Meinshausen, M., Ray, D.K., Karoly, D., Meinshausen, N., Frieler, K., 2019. The effects of climate extremes on global agricultural yields. Environ. Res. Lett. 14 (5), 054010.

Wall, J., Douglas-Hamilton, I., Vollrath, F., 2006. Elephants avoid costly mountaineering. Curr. Biol. 16 (14), 527–529.

Walpole, M.J., Ndoinyo, Y., Kibasa, R., Masanja, C., Somba, M., Sungura, B., 2004. An Assessment of Human Elephant Conflict in the Western Serengeti. Unpublished Report, Frankfurt Zoological Society, Arusha, Tanzania.

Williams, P.A., Simpson, N.P., Totin, E., North, M.A., Trisos, C.H., 2021. Feasibility assessment of climate change adaptation options across Africa: an evidence-based review. Environ. Res. Lett. 16 (7), 073004.

Wilson, S., Davies, T., Hazarika, N., Zimmermann, A., 2013. Understanding spatial and temporal patterns of human-elephant conflict in Assam, India. Oryx 49, 140–149.