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A Socio-Ecological Approach to Understanding How Land Use Challenges Human-Elephant Coexistence in Northern Tanzania

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Abstract: A globally rapid land use/land cover change (LULC) in human-transformed landscapes alters the interface of human-wildlife interactions due to shifting socio-ecological and environmental pressures. Understanding these shifts is crucial for mitigating repeated negative interactions that escalate conflict states between people and wildlife. This study aimed to understand LULC changes over 30 years (1989–2019), with more recent spatio-temporal patterns of high pressure at the human-elephant interface, and potentially underlying environmental and human-driven factors that affect elephant movement patterns. We analyzed a dataset of 923 human-elephant conflict occurrences, mainly crop foraging incidents, in the Enduimet Wildlife Management Area (EWMA) between the years 2016 and 2020 and combined these data with LULC for year 2019 to understand potential drivers of conflict and assess how agricultural land and settlement have increased over time. We further used GPS datasets of elephants collared between 2019 to 2020 to understand elephant movement patterns in changing land use types. Landsat image analysis revealed that 41% of the area had been converted into farmlands and settlements within the last three decades, which creates elephant-intolerant habitats and the potential to increase pressure at the human-elephant interface. Collared elephants using EWMA moved through all land use types and did not avoid settlements, although they moved through these at higher speeds, reflecting perception of risk. Elephants travelled slightly more slowly in farmland, likely reflecting the availability of foraging opportunities. Our analysis shows that human-induced LULC changes and the encroachment into elephant habitats have resulted in spatially and temporally predictable increases in HEC in EWMA, driven by the proximity of farmlands and protected areas (PAs), so that incompatible land uses are the principal drivers of damage to human livelihoods and increased risks to Tanzanian (and Kenyan) natural capital. Communities in Enduimet urgently need support to increase the effective distance between their farming activities and the PAs. Village-level crop protection and small-scale land-use planning around PAs are important first steps to halt an escalating conflict situation but need to be supported with longer-range strategies that separate incompatible land-use types and encourage the cultivation of alternative crops and livelihood diversification.

Keywords: Enduimet WMA; *Loxodonta africana*; GPS collars; human-wildlife conflicts; land use-land cover change; interviews

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1. Introduction

Humans and wildlife have co-existed over millennia, but increasing human activities have tipped the scale towards negative interactions due to increased demands on natural resources [1]. These activities, mainly settlements, farming and livestock-keeping adjacent to protected areas (PAs), have recently intensified negative interactions and damaged community livelihoods [2,3]. In Tanzania, as elsewhere, these intensified negative interactions are termed human-wildlife conflict (HWC), a serious conservation concern because of the significant risks to human lives and livelihoods and consequent impacts on the sustainability of wildlife conservation initiatives [4].

Land Use/Land Cover (LULC) changes and human encroachment into PAs affect ecological systems and wildlife distribution, thereby influencing the spatial patterns of HWC [5,6]. For example, in the Maasai Mara–Serengeti ecosystem in Kenya and Tanzania, seven wild ungulate species declined by 25% as a result of land-use changes [7,8]. Climate change and increasing climate variability influence food and water availability for wild herbivores [9], resulting in increased movements and likelihood of human-wildlife interaction. In the Trans-Himalayan region, Nepal, Aryal et al. [10] found that blue sheep (*Pseudois nayaur*) foraging areas shifted towards lower altitudes as a result of land-use changes, which correspondingly drew leopards (*Panthera uncia*) from higher altitude habitats and increased HWC. These problems are predominantly true for species that require large home ranges, such as the African elephant (*Loxodonta Africana*) [11]. Populations that once moved freely through a mosaic of natural vegetation types are now confronted with a man-made labyrinth of barriers that fragment formerly expansive natural landscapes [12].

The interface between the African elephant and humans is becoming particularly strained. Elephants are classified as endangered under the IUCN red list 2020 [13], and form a vital part of range state natural capital and ecosystem function [14,15], but in Tanzania, elephants range both within PAs and on community lands where they may cause damage to crops and property and sometimes human injury or death [16]. Elephant home ranges are often constrained by human presence, and their spatio-temporal movements across landscapes might often drive shifts at the human-elephant interface that underlie HEC occurrences [17]. Elephant movement speeds are reliable indicators of the level of perceived risk [18], as elephants move more quickly in areas that may be dangerous for them [18], but few studies have related movement patterns and conflict hotspots. [18]. Unfortunately, many HEC studies still rely solely on survey questionnaires that are prone to bias, as losses can be exaggerated by respondents, especially if encounters have been traumatic [16,19,20]. Understanding how LULC changes and elephant space use drive HEC can yield crucial insights for developing effective mitigation and biodiversity conservation strategies [17,21].

Increasing HEC incidences in Tanzania and the knowledge gap about the main drivers of HEC motivated us to conduct this study in the Enduimet Wildlife Management Area (EWMA). Despite the importance of HEC assessment, environmental correlates of conflict, including the effects of natural and anthropogenic parameters, have rarely been connected to detailed elephant spatial and temporal movement patterns. Further, little is known about how anthropogenic activity expansion has impacted elephant movement patterns and HEC in both protected and unprotected areas such as EWMA and other parts of Tanzania. The increasing human population has accelerated land use changes (e.g., settlements, agricultural land) and reduced natural vegetation, and increased both the absolute number of interactions between humans and elephants and the likelihood of conflict. Thus, the assessment of a linkage between LULC changes and HEC spatio-temporal distribution is important in developing sustainable solutions for conserving and protecting elephant populations and human livelihoods.

In this study, we applied Geographical Information System (GIS) and Remote Sensing techniques to quantify LULC changes over 30 years. We also analysed elephant movements using transboundary GPS collar locations in Kenya (Amboseli National) and Tanzania (Enduimet Wildlife Management Area; EWMA) of three male elephants between the years

2019 and 2020. We combined this information with household data on HEC collected during the survey, as well as with a HEC dataset collected by OIKOS literature (HEC reports) and participatory field assessments, to evaluate pressure at the human-elephant interface and investigate environmental correlates of "conflict", including the relative effects of natural and anthropogenic influences in EWMA. We aimed at capturing long-term information on LULC changes for the years 1989, 1999, 2009 and 2019, and to overlay more recent elephant movements and LULC for the year 2019 in this changing landscape and assess the spatiotemporal distribution of HEC and their underlying drivers. Specifically, we aimed to (i) map LULC changes between 1989 and 2019 in the EWMA, (ii) model the most important environmental and anthropogenic predictors of HEC, (iii) estimate male elephant home ranges in relation to HEC hotspots areas, and (iv) analyze the spatio-temporal patterns of HEC and elephant movement speed under different land use based on the 2019 classified LULC map. We hypothesized that (i) farmlands and settlements have increased in the EWMA over the last three decade and escalated the potential for HEC, (ii) crop raiding events would increase during the dry season, when wild food resources become limited, (iii) HEC incidents would increase over the years as farmlands expanded, (iv) HEC incidents would be high in areas of high Normalized Difference Vegetation Index (NDVI) values since elephants prefer rich foraging areas, and (v) elephant movement speed would be high in human-dominated areas.

2. Materials and Methods

2.1. Study Area

The Enduimet Wildlife Management Area (EWMA) covers 752 km^2 [22], within the Longido District, in the Arusha Region. The area is bordered by Kilimanjaro National Park (KINAPA) to the South-east, the Tanzania-Kenya political boundary to the north and the Ngasurai plains to the west (Mariki et al., 2015). The EWMA was established in 2005 under the Tanzania wildlife policy of 1998 and comprises nine villages concentrated along the productive slopes of Mt. Kilimanjaro [23] (Figure 1). As many as 600 elephants utilize EWMA during the dry season [24], and it represents an important wet season sanctuary for elephants and other species, including wildebeest (*Connochaetes taurinus*), lions (*Panthera leo*), zebras (*Equus quagga*) and African buffalos (*Syncerus caffer*) [25].

The EWMA comprises the Kitendeni wildlife migratory corridor (KWC), which connects the Kilimanjaro in Tanzania and Amboseli National Parks in Kenya [26], and serves as a major transboundary migratory corridor for many wildlife species [27]. This remains the only formally protected wildlife corridor that links EWMA to other PAs such as Natron Game Controlled Area, Arusha and Mkomazi National Parks [28]. The corridor is, however, under threat following the rapid expansion of human activities and changes in land use over the years [7]. The EWMA contains arable and fertile lands with high agricultural potential and a rapidly increasing number of human settlements, in particular the villages of Tingatinga, Elerai, Lerang'wa, Kamwanga and Olmolog [23]. The human population in EWMA is about 57,000 people, having increased by 30% between 1988 and 2017 [24,29]. Although traditionally the resident Maasai are nomadic pastoralists, agriculture and tourism-related activities are becoming an important source of income [30]. The average annual rainfall of EWMA ranges between 300–600 mm, daily average temperatures between 30–35 °C, and it covers an elevation ranging between 1230–1600 m [31]. The big rainy season lasts from February to May, while the small rainy season lasts from June to November [23]. Agro-pastoralists practice small-scale farming concentrated during the short rains, and plant crops that mature quickly and are drought-tolerant, such as maize (*Zea mays*) and beans *(Phaseolus vulgaris)* [7]. The natural vegetation is primarily comprised of mixed *Acacia* woodlands, including *Acacia commiphora* bushland, *Acacia tortilis* savannah and *Sporobolus* short grass plains, typical of semi-arid East African savannah [7].

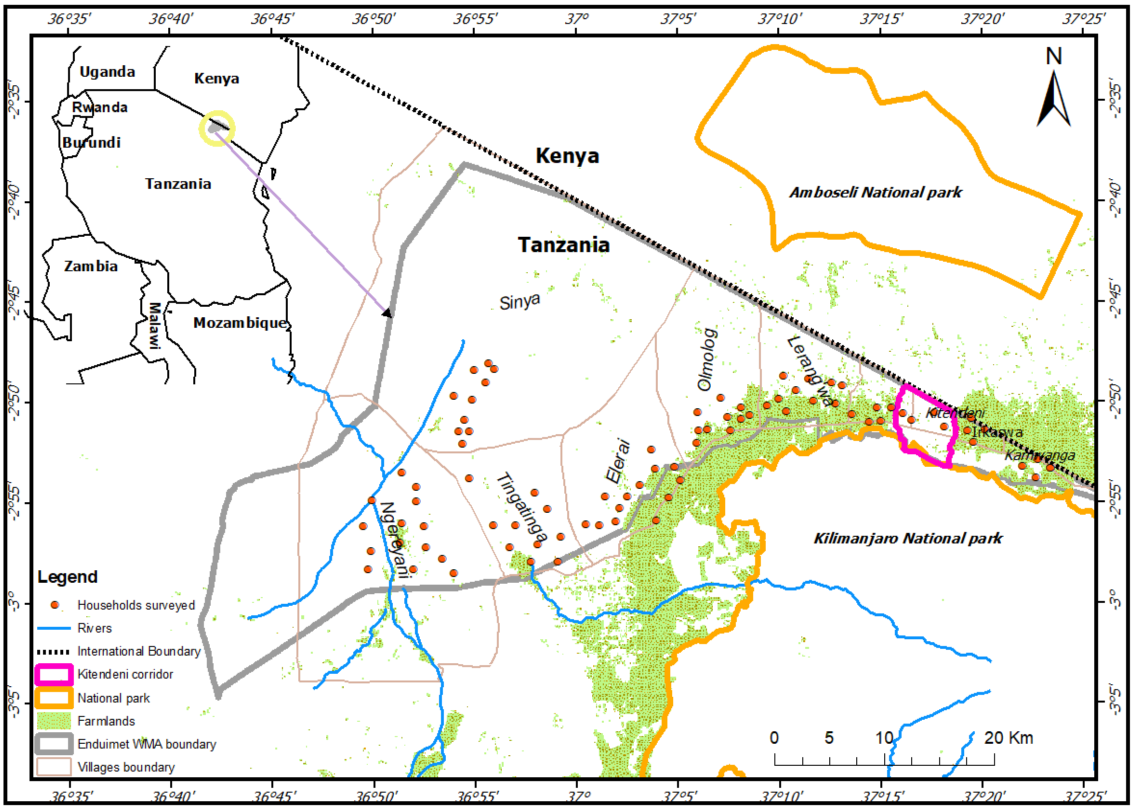

Figure 1. Map of the study area showing the location of households surveyed ($n = 96$) across different villages from March 2019 to June 2019 as well as the Kilimanjaro and Amboseli National Parks, Enduimet Wildlife Management Area (EWMA) and farmlands within the EWMA, Tanzania, based on the map of 2019.

2.2. Remote Sensing Data for LULC Analysis

In order to analyze LULC changes over the years 1989, 1999, 2009, and 2019, we used time-series pairs of Landsat images, namely Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper plus (ETM) and Landsat 8^{+} with two sensors: the Operational Land Image (OLI) and Thermal Infrared Sensor (TIRS). All images were visually interpreted and processed to map LULC. The satellite images downloaded with 30 m resolution were freely accessed from USGS earth explorer (http://www.usgs.gov, accessed on 29 March 2021) (Table A1). Images were captured during the dry season with less than 10% cloud cover, imported in ArcGIS 10.6 and georeferenced for processing and analysis using the World Geographical System (WGS) 1984, and projected to Universal Transverse Mercator (UTM) Zone 37S. Before classification, we performed image pre-processing, such as layer stacking radiometric and geometric correction, to improve the quality of the image by minimizing various radiometric and atmospheric errors [11]. Visual interpretation and high-resolution imagery, such as GeoEye (1.36 m × 1.36 m) and/or SPOT (20 m × 20 m) on Google Earth, were used to determine signature files to be used in classification based on previous studies in the Serengeti ecosystem [32] and Kilombero valley floodplain, south-eastern Tanzania [33]. Training signatures for the nine LULC classes, including agriculture, settlements, bare ground, bushland, forest, grassland, woodlands, water, and wetland (Table A2) were visually interpreted and then digitized as polygons. All Landsat images were classified by using Maximum Likelihood Classification (MLC) [34] and verified on the ground. Post image classification was performed to determine the accuracy of images classified using a confusion error matrix [35,36] and to validate remotely sensed data by comparing classified images with the provided ground-truthing data [37].

2.3. Household Survey for Primary HEC Hotspots

We used a semi-structured questionnaire survey (Supplementary File S1) adapted from Punch [38] to collect data on the locations and numbers of HEC incidents in eight administrative villages (Figure 1). A total of 96 households located at least 1 km apart from each other were selected using a systematic random sampling protocol [39] and interviewed about HEC incidents in their respective villages from the years 2016 to 2020. We interviewed respondents aged >25 years who had been living in the area for more than 5 years. In addition, we asked elders (>55 years) of each village to recall the trend in LULC changes and the nature of HEC incidents that happened in the area over the past 5 years to complement data from classified Landsat satellite images on LULC. We also consulted four EWMA staff to complement our knowledge on HEC incidences that had occurred in the area over the past 5 years. Each respondent was interviewed only after verbal consent to participate was given.

2.4. Secondary Data for HEC and Environmental Dynamics

Data on the spatial location of HEC in EWMA, in particular crop forage incidents, were collected between May 2016 and May 2020 by the Tanzania Wildlife Research Institute (TAWIRI) (www.tawiri.or.tz, accessed on 12 August 2020) and OIKOS East Africa (http://oikosea.co.tz, accessed on 17 June 2020 under the EU-funded project CONNEKT (Greater Kilimanjaro Initiatives to enhance community participation in sustainable conservation of the trans-frontier ecosystem and wildlife). Each HEC incident was recorded as a unique event, and information about the location of crop raids, date and time, name of the village, as well as crop type affected, were collected. The distances of all HEC locations to the park boundaries, nearest road networks and the nearest rivers were obtained using nearest tool in QGIS version 3.6. The elevations of the HEC locations areas were extracted from a Digital Elevation Model (DEM) (https://www.usgs.gov, accessed on 1 May 2021 having a spatial resolution of 30 m [40]. Average NDVI values for the years 2016 to 2019, related with occurrences of HEC and elephant home ranges, were derived from Moderate Resolution Imaging Spectroradiometer (MODIS) **(**https://modis.gsfc.nasa.gov**,** accessed on 13 September 2021) (Table 1).

Table 1. Major environmental variables that were used in our model to test whether they influenced human-elephant conflict occurrences were collected in the Enduimet Wildlife Management Area, Tanzania, from 2016 to 2020. NDVI = Normalized Difference Vegetation Index, season = time of the year that is distinguished by special climate condition (wet and dry), HEC = human-elephant conflict.

Variable	Unit	Category	Range (Min–Max)
Dependent variable			
HEC occurrence		categorical	0 and 1
Independent variables			
Distance from river	km	continuous	0–24
Distance from main road	km	continuous	0–13
Distance from protected area	km	continuous	0–46
Distance from farmland	km	continuous	0–18
Distance from settlement	km	continuous	0–60
Elevation	m. a. s. l.	continuous	1125–5120
Year		numerical	2016–2020
NDVI	values	numerical	0–1
Season		categorical	wet and dry
Time of day		categorical	night and day

2.5. Spatial and Temporal Distribution of Elephants

We used 52,488 GPS locations of three male elephants ranging in the EWMA between 2019–2020, collected from collars fitted by the Amboseli Trust for Elephants (ATE). Collared elephants were based on known IDs from Amboseli elephant families studied since 1972 [41].

All males were of dispersal age (range 8–19, mean 13 years old) and were either still in association with their natal family or had known dispersal dates within the previous 6 months. GPS collars (GSM IPO-95 supplied by Savannah Tracking Ltd., Kilifi, Kenya) recorded hourly location fixes and had been monitored for fit and wear during observations of target elephants. Permissions to deploy collars had been obtained from Kenya Wildlife Service.

2.6. Data Analysis

QGIS version 3.6 software was used for change detection statistics and to determine changes in LULC between pairs of consecutive classified images, i.e., from 1989 to 2019. All datasets on HEC from both OIKOS and our conducted field questionnaires were combined before analysis, as the same methodology, design and tools were used. We examined the relative influence of key underlying correlates using a binary multiple logistic regression incorporating environmental (NDVI, elevation, distances from PAs, main road network and rivers) and anthropogenic variables (the proportion of land converted to agriculture and settlement (Table 1). Before running the model, variables showing multicollinearity, i.e., having a Variance Inflation Factor (VIF) greater than 10, were identified and dropped from the model [42]. We examined annual, seasonal and time of day effects on crop foraging incidents using the Kruskal-Wallis or the Mann-Whitey U-test. We measured spatial autocorrelation of incidents using Global Moran's I function and identified incident hotspots using Kernel Density Estimation (KDE) and Gedis-Ord Gi algorithms in ArcMap 10.6 software. Next, we combined the KDE surface with different LULC classes to generate a hotspot map. We estimated home range for each male elephant using 100% minimum convex polygon (MCP100%) and 95% fixed KDE following procedures described by Kikoti et al. [25]. KDE was implemented using Hawth's tools in ArcMap 10.5 software and overlaid with the dataset on crop incidents. We determined elephant travel speeds and the percentage of GPS fixes within each land use class of the EWMA. A one-way ANOVA test (Welch's) was used to determine the difference of studied parameters (settlement, farmland and other areas of EWMA). All statistical analyses were performed using R version 3.4.1 (https://www.r-project.org, accessed on 15 January 2022) and at a 5% level of significance ($\alpha = 0.05$) unless otherwise stated.

3. Results

3.1. Land Use / Land Cover (LULC) Class Changes

We found that thirty years of LULC had converted EWMA from a grassland-dominated ecosystem to one in which wildlife-incompatible agriculture and settlements had more than doubled. This change was mainly due to the rapid conversion of 1042 ha of forest and 17,711 ha of grassland to farmland within the last 10 years (Table 2). Bushland and woodland cover remained overall stable, while bare ground declined slightly over time from 2009 to 2019 (Table 2). Our results showed a high rate of agreement between the user's accuracy and producer's accuracy in terms of grassland, woodland, and water cover changes across all images with Kappa Indices of Agreement of 0.86, 0.87, 0.79 and 0.91 for the four periods under investigation, which is similar to the standard land cover mapping accuracy of 85–90% [32]. Above 0.75 Kappa is the minimum acceptable interrater agreement [43]. Therefore, this makes us confident in the analytical process.

3.2. Influence of Environmental and Anthropogenic Factors on HEC

Environmental factors that significantly influenced HEC occurrence were low elevation, proximity to settlements, farmlands and protected areas. Furthermore, based on interviews and existing reports, HEC occurrence across the entire study period was closely linked with higher average NDVI values, particularly in the wet season, confirming the elephants' preference for rich and productive vegetation. Distances from roads and rivers (Table 3) showed a non-significant relationship with HEC occurrence in our study area. Elephant raids occurred most often in farmland within 20 km of PAs (80% of incidents), concentrating on agricultural areas along the KWC and close to the villages of Tingatinga and Ngereyani. A small number of raids (20%) occurred between 21 km to 40 km away from the EWMA boundary (Figure 2).

Table 2. Land Use/ Land Cover (LULC) classes (in ha and % coverage) between 1989 and 2019 in the Enduimet Wildlife Management Area, Tanzania (EWMA). Cover classes were categorized according to ([32,33]. See also Table 1.

LULC Classes	LULC Coverage							
	1989		1999		2009		2019	
	ha	%	ha	%	ha	%	ha	%
Agriculture	25,999	13.47	28,698	14.86	35,017	18.14	50,685	26.25
Bare ground	3291	1.70	2827	1.46	2408	1.25	710	0.37
Bushland	24,935	12.91	34,251	17.74	24,020	12.44	26,312	13.63
Forest	2949	1.53	991	0.51	1042	0.54	86	0.04
Grassland	120,746	62.54	101,845	52.75	102,059	52.86	84,348	43.69
Settlement	10,350	5.36	18,002	9.32	21,060	10.91	24,599	12.74
Woodland	4026	2.09	5507	2.85	5293	2.74	5636	2.92
Water bodies	0	0.01	8	0.01	4	0.01	3	0.01
Wetland	777	0.40	944	0.49	2170	1.12	694	0.36

Table 3. Binary multiple logistic regression analysis results of variables influencing human-elephant conflict occurrences (n = 923), collected by Oikos East Africa, household interviews (n = 96), collared elephant home ranges (n = 3) and grey literature reports in the Enduimet Wildlife Management Area, Tanzania, from 2016 to 2020. PA = protected area, NDVI = Normalized Difference Vegetation Index.

Variable	Estimate	SE	*Z*	*p*
(Intercept)	25.01	1.33	3.61	0.001
Elevation (m)	−0.01	−0.03	−4.26	0.001
Distance from farmland (km)	−1.13	0.00	−2.84	0.004
NDVI	16.41	1.05	2.12	0.027
Distance from PA (km)	−0.81	0.31	−3.09	0.007
Distance from river (km)	−0.28	0.32	−1.10	0.331
Distance from settlement (km)	−0.46	0.29	2.06	0.037
Distance from road (km)	−0.02	0.25	−1.53	0.321
Distance from river * from road	0.01	0.01	0.92	0.359
Distance from farmland * from PA	0.01	0.01	2.31	0.021

Note: * interaction between two variables.

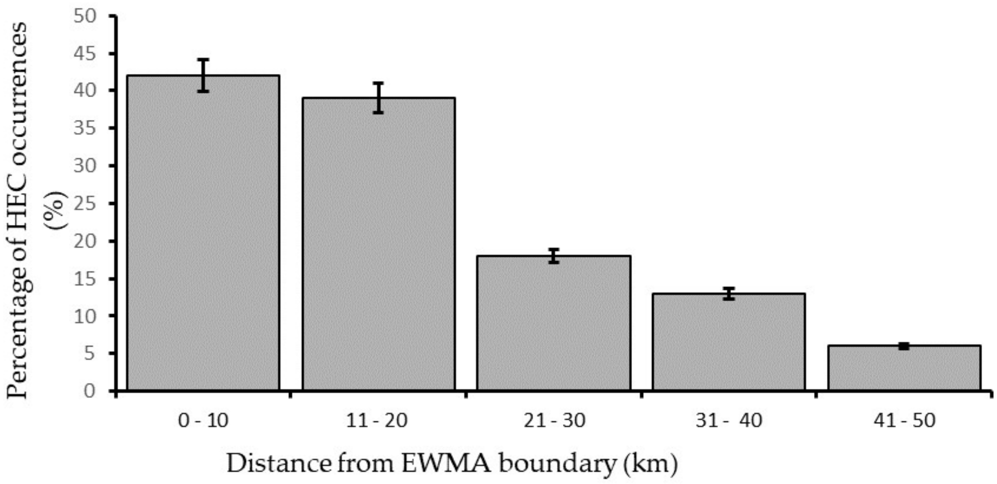

Figure 2. Percentage of human-elephant conflict (HEC) occurrence (n = 923) within varying distances from 0 Enduimet Wildlife Management Area (EWMA) boundary (in km), as reported between 2016–2020.

3.3. Spatio-Temporal Patterns of HEC and Hotspot Mapping under Different LULC

A total of $n = 923$ crop foraging incidents were recorded by Oikos East Africa between May 2016 and May 2020 across the eight villages in EWMA, with an annual mean (±SD) of 185 (±173). The lowest ($n = 56$) and the highest ($n = 482$) number of incidents took place in 2016 and 2019, respectively, but there was no significant trend across the years ($p > 0.05$). Although crop losses caused by elephants occurred throughout the year, most incidents (55%) were recorded during the dry season, from June to November, when wild forage resources for elephants decrease in quality. There was a trend of more incidents being documented during the harvest periods of May (26%) and June (25%) (Figure A4), while lower incidents were observed in April (3%) and October (2%), albeit not significantly different ($U = 10.50$, $Z = 0.42$, $p = 0.69$). Further, there was no significant trend across years 2016 to 2020 (H (4) = 5.55, $p = 0.24$). The majority (82%) of the recorded crop foraging incidents took place during the night and were concentrated across six clusters within Tingatinga and Ngereyani, showing strong spatial autocorrelation (Moran's $I = 0.34$, Z-score = 33.8, $p < 0.0001$; Figure 3).

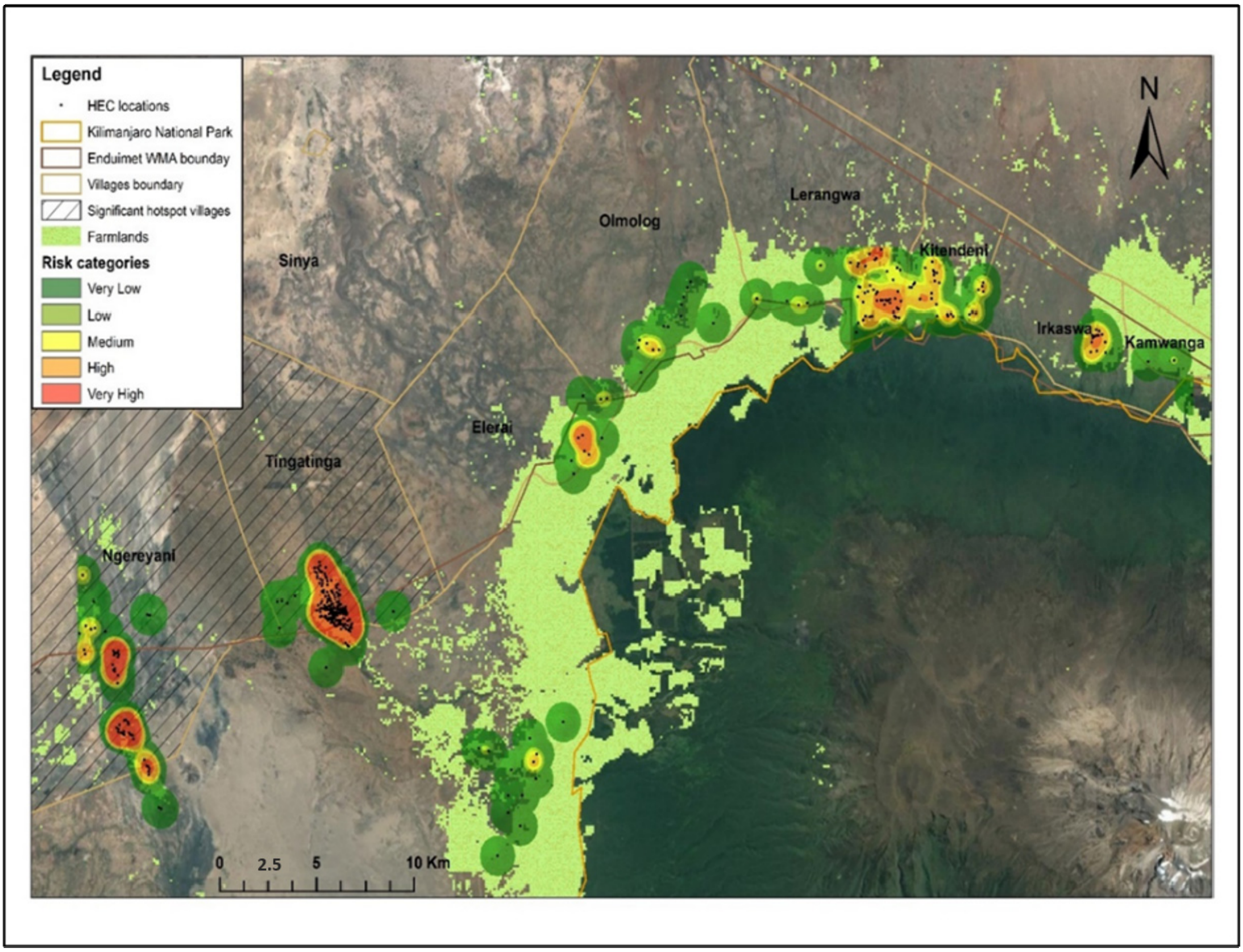

Figure 3. Heat map of areas with a high risk of being a crop foraging hotspot for elephants in the Enduimet Wildlife Management Area and close farmlands adjacent to the southern part of EWMA, Tanzania ($n = 923$), generated from HEC data collected by OIKOS East Africa and interviews ($n = 96$) between the years 2016 to 2020.

3.4. Elephant Home Range and Habitat Use

From more than 52,488 GPS fixes collected from three male collared elephants known to the Amboseli Elephant Research Project between 2019 to 2020, male elephants spent most of their time (48% of total recorded fixes, $p < 0.05$) in Amboseli National Park (Kenya) and 10% of their time in the EWMA (Tanzania). In agreement with other studies, elephant home range sizes were highly variable between individuals and seasons, but no significant pattern was visible ($p > 0.05$ for all variables; Table A3 and Figures A1–A3). In the EWMA, 27% of elephant GPS fixes were recorded in agricultural areas, while 38% and 34% were found in grassland and bushland, respectively. Elephant home ranges overlapped with farmland in the villages of Tingatinga and Ngereyani, where 23% of the GPS fixes were less than 2 km away from settlements and farmlands, and 27% of the GPS fixes around Lerang'wa, and Kitendeni villages were recorded near farmland (within the buffer zones or 0–20 km from the park boundary) (Figure 4).

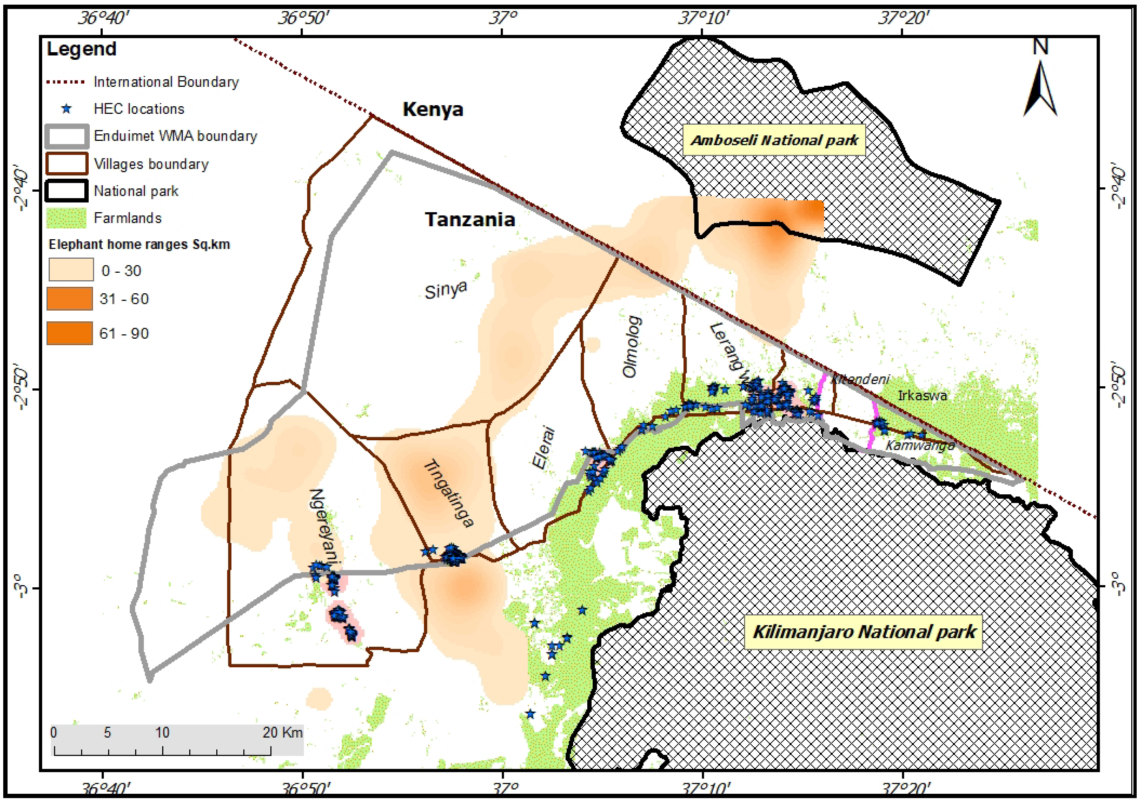

Figure 4. Home ranges for three collared male elephants (n = 52,488) in the EWMA and close farmlands adjacent to the southern part of EWMA from July 2019 to September 2020 calculated using Kernel Density Estimation (KDE).

We further found a statistically significant difference ($F = 5.543$, $p = 0.004$) in the average speed of elephants between farmland and settlements and other areas of EWMA. The collared male elephants moved almost 10% significantly slower in farmlands (0.83 km/h) compared to areas near settlements (1.08 km/h) or other areas of EWMA habitats (1.06 km/h) (Figure 5).

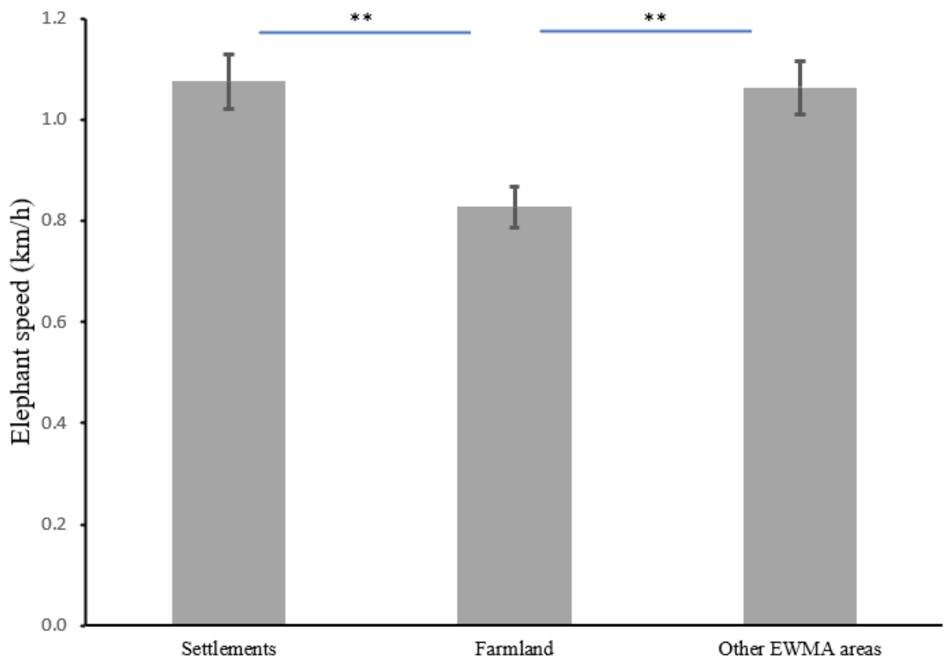

Figure 5. Average (±SE) speed of three male elephants collared in Amboseli National Park, Kenya, who also ranged in the Enduimet Wildlife Management Area (EWMA) in farmlands and settlements from 2016 to 2020. Bar plots with an asterisk are significantly different at $p < 0.01$ based on a Games-Howell Post-hoc Test.

4. Discussion

4.1. Land Use/Land Cover Change Effects on Elephants in EWMA

There was persistent spatial and temporal LULC change in the EWMA throughout the thirty years of assessment. Grassland, bushland, and agriculture together formed 90% of the EWMA in 1989. The first two cover classes experienced the greatest reduction, to 84% in 1999, 82% in 2009 and finally 72% in 2019. Agriculture had a rapid increase during the same years (13–26%), doubling in the area from 1989 (25,999 ha) to 2019 (50,685 ha). The slight increment of 51 ha of forest area between 1999 and 2009 was likely due to a compensatory afforestation and plantation program [7]. Our findings that a large proportion of natural vegetation (152,656 ha in 1989 to 116,382 ha in 2019 or 79% in 1989 to 60% in 2019) was transformed to farmland and settlements are consistent with other studies in eastern Africa [44], indicating that anthropogenic activities are the main driver for LULC changes [8,32]. The total human population of the EWMA was around 47,103 people in 2012, with an average annual growth rate of 3% [45], which might have led to an increased demand for natural resources and land. The establishment of plantations and settlements in the EWMA, as well as intense livestock grazing practices, might have blocked the traditional migratory route of elephants from east to west [23,24,46]. However, even if elephants can navigate these obstacles, these practices usually increase the contact between elephants and people and, thereby, enhance the potential for damaged livelihoods [47–49]. In addition, agriculture-supporting policies encouraged the expansion of agriculture between 2009 and 2019 in the EWMA [50], causing changes in grasslands and forest cover. Globally, the human population is projected to increase in the coming decades, particularly in Africa [51] and likely also in the EWMA [52], threatening the survival of the elephant populations and their habitats. Wildlife tends to disappear when anthropogenic activities cover 25–50% of savanna landscapes [53], and our results revealed that settlement and agriculture together encompassed about 37% of the EWMA land in the year 2019. In Ghana, savanna reserves surrounded by human settlements have lost a large number of wildlife species over time [54], and we might be seeing similar trends in EWMA. The growth of human populations around PAs may further have strong negative impacts on large mammals and biodiversity through poaching, deforestation, and habitat encroachment, as was shown recently in a human-dominated landscape in North Bengal [55] Mole National Park in Ghana and Tarangire National Park in Tanzania [54].

4.2. Environmental and Anthropogenic Variability Determines HEC

We found a strong positive and significant relationship between NDVI and HEC occurrence, in line with other studies [56,57], as both elephants and farmers select areas of higher rainfall, and farmers effectively create new foraging opportunities for elephants within these already preferred areas [56,58,59]. Moreover, we found that HEC decreased with increasing elevation, likely as elephants prefer flat lands and lowland forests compared to highlands [60]. In contrast to other studies [61,62], which claimed that decreased water and food availability in protected areas could lead to higher HEC, we found a non-significant relationship between HEC occurrence and water body distribution in EWMA. The spatial resolution at which we sampled might have been too coarse and did not take artificially added water holes or seasonal water bodies into account [63]. While roads and small pathways open up areas for human passage and increase the probability of contact between humans and elephants [64], we did not find any significant positive or negative relationship of HEC with roads. This might be due to the fact that EWMA vegetation is quite open, and there is no need for elephants to use roads in otherwise inaccessible terrain [22].

4.3. Spatio-Temporal Patterns of HEC

Our results showed the tendency of increasing HEC incidents into the dry season in June, when crops such as *Zea mays* (maize), *Phaseolus vulgaris* (beans), *Solanum lycopersicum* (tomatoes) and *Triticum* spp. (wheat) are maturing and harvested [8]. At this time, elephants raid farmlands for nutritious and palatable crops despite the availability of natural forage resources within protected areas [65,66]. Additionally, we observed spatially clustered HEC incident areas, mainly close to protected area boundaries in the EWMA, as has been widely reported across Africa's protected areas [47,49,67,68]. Our HEC hotspots in Ngereyani and Tingatinga villages reflect the proximity of vast plantations of maize and beans as well as bushlands, a mixed tree and grass system dominating the southern parts of the EWMA, which represent an attractive habitat for elephants and potentially increased the HEC incidences in the area. The presence of dense vegetation and open grassland near farms and settlements, along with available patches of forest outside the PA in our study, may have assisted elephant movements and facilitated crop raiding. Moreover, the presence of a permanent river flowing from Tingatinga to Ngereyani is an important water source for villagers and wildlife and might have influenced the two observed HEC hotspots areas [69].

4.4. Influence of Elephant Home Ranges on HEC

We found that elephants using EWMA demonstrated less constrained movements during the wet season, albeit not significant, but had an influence on HEC as elephants do not have to stay close to surface water bodies to drink, which is crucial for lactating females and contributes to sexual segregation in elephants during the dry season [70]. Although elephants mostly used protected area habitats on both sides of the country border, the foraging opportunities in farmland were reflected by the proportion of elephant GPS fixes in agricultural areas and by relatively low walking speed [18,71].

This cluster of low elephant moving speeds likely reflects foraging opportunities available in farmland, but as these data were not overlaid with crop availability data due to different resolutions, we could not identify if any of the collared elephants were involved with identified crop foraging events.

On the other hand, elephants travelled at the same speeds in settlement areas and in other EWMA areas. Generally, male elephants have higher risk tolerance and a higher payoff for crop foraging [72], and this trend was visible in our collar data. Understanding that crop foraging is only a small part of an elephant's ranging behavior is important for developing sustainable solutions, as our collared elephants spent 90% of their time in other areas (the rest of EWMA that is neither settlement nor farmland) rather than near farms [73]. Our results are further in line with [74], who found HEC in Rombo district close to Kilimanjaro National Park mainly occurring during the night. In addition, our study revealed cold spots for HEC in areas that were cultivated with crops less preferred by elephants, such as Taro (*Colocasia esculenta*), Tumeric (*Cuscuma longa*), Chili (*Capsicum* sp.), Eggplant (*Solanum* sp.) [67], which are not currently planted by farmers in EWMA, highlighting a potentially robust solution against HEC. Areas of high human population and a decrease of suitable land were the best predictors of HEC in Mozambique [75], where it was found that areas with a human population density of <60 people/km^2 had lower HEC incidences than areas with higher human population densities. At low population densities, there is less interaction between humans and elephants, but also human driven destruction on elephant habitats and migratory routes might be lower [76]. Unfortunately, our time span for land cover change and GPS collar data did not cover exactly the same time span, during which conflict occurrences were assessed, making it difficult to relate changes in LULC to HEC incidences over time. Further, reports and interviews might have exaggerated damage extent as farmers receive reimbursement only for certain damage to their crops. Nevertheless, we think that our socio-ecological approach is highly valuable in identifying spatial and temporal conflict risk zones and finding underlying factors, which can be applied for further land management actions. Nevertheless, our study provides a spatio-temporal HEC risk-map, and we were able to show that our combination of cross-boundary long-term remote sensing imagery series with unpublished reports on crop raids and GPS elephant movement data provide a valuable resource for HEC predictions and land use planning strategies for in the EWMA of northern, Tanzania.

5. Conclusions

Our analysis showed that human-induced LULC changes and the encroachment into elephant habitats have resulted in spatially and temporally predictable increases in HEC in EWMA. Particularly, forests and grasslands have been converted into agricultural land and settlements over the last three decades, which may have increased the competition between elephants and humans. As the majority of farms in EWMA are located close (0–20 km) to the protected areas, which likely stimulated crop foraging and escalated conflict situations, we propose to enforce buffer zones and effectively increase the distance of human settlements and farmland from protected areas and elephant habitats. Local farmers urgently need village-level crop protection, along with small-scale land-use planning around protected areas, as an important first step to halt an escalating conflict situation but need to be supported with longer-range strategies that separate incompatible land-use types and encourage the cultivation of alternative crops and livelihood diversification [67]. We highlight that movement speed by elephants can be a crucial indicator for potential foraging hotspots and associated conflicts. Tracking data can be used to delineate well-used movement paths, and together with suggested cultivation distances from such paths, land-use policies can be informed at the governmental level. This will minimize further agricultural encroachment and keep corridors and habitats accessible to elephants while diminishing HEC [77] and protecting rural livelihoods. We were able to show that our combination of cross-boundary long-term remote sensing imagery series with unpublished reports on crop raids and GPS elephant movement data provide a valuable resource for HEC predictions and land use planning strategies in northern Tanzania.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/d14070513/s1, File S1: Questionnaire for local respondents.

Author Contributions: J.E.S.: conceptualization, methodology, images processing, formal analysis, writing original draft, reviewing, and editing, D.V.: formal analysis, reviewing and editing. C.L.: formal analysis, formatting, and editing, V.F.: formal analysis, reviewing, G.G. for statistical analysis and A.C.T.: Conceptualization, methodology, reviewing, supervision and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available to due to privacy.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationship that could have influenced the work reported in this paper.

Appendix A

Table A1. Details of the Landsat images used for land use/land cover mapping during our study in the Enduimet Wildlife Management area, Tanzania, for the years 1989, 1999, 2009 and 2019 (source: http://www.usgs.gov, accessed on 29 March 2021).

Acquisition Date	Scenes (Path/Row)	% Cloud Cover	Sensor	Data Source
8/24/1989	139/42	<10%	TM	USGS
7/2/1999	138/42	<10%	ETM+	USGS
7/11/2009	137/062	<10%	ETM+	USGS
8/7/2019	138/062	<10%	OLI & TIRS	USGS

Table A2. Description of Land use/Land cover (LULC) classes used in our analysis modified from a classification system by [32,33] in the Enduimet Wildlife Management Area, Tanzania, from 1989, 1999, 2009 to 2019.

LULC Types	LULC Description
Agriculture	Land actively used to grow crops (seasonal and permanent)
Bare ground	No vegetation (exposed rock outcrops and bare soil)
Bushland	Dominated by multi-stemmed plants from a single root base and woody cover
Forest	>50% canopy cover of woody plants of $\geq$5 m height
Grassland	<10% cover of sparse woody plants, dominated by continuous herbaceous cover
Settlement	Urban and rural settlements (houses, roads, infrastructure)
Water	Water bodies, mostly permanent (inland water)
Wetland	Marshes or swamps; saturated land
Woodland	<50% canopy cover of woody plants of $\geq$5 m height

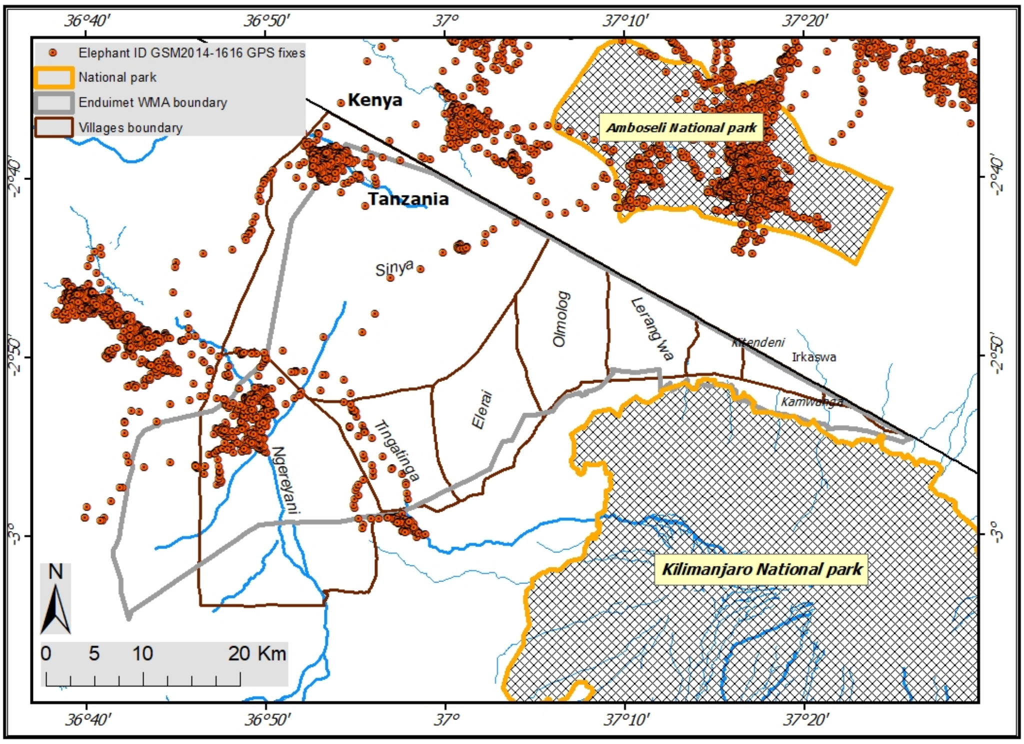

Figure A1. Spatial distribution of one collared elephant with the ID GSM2014-1616 (n = 17,452) in the Amboseli National Park in Kenya, in the Kilimanjaro National Park and Enduimet Wildlife Management Area (EWMA) in Tanzania. Source: Amboseli Trust for Elephants.

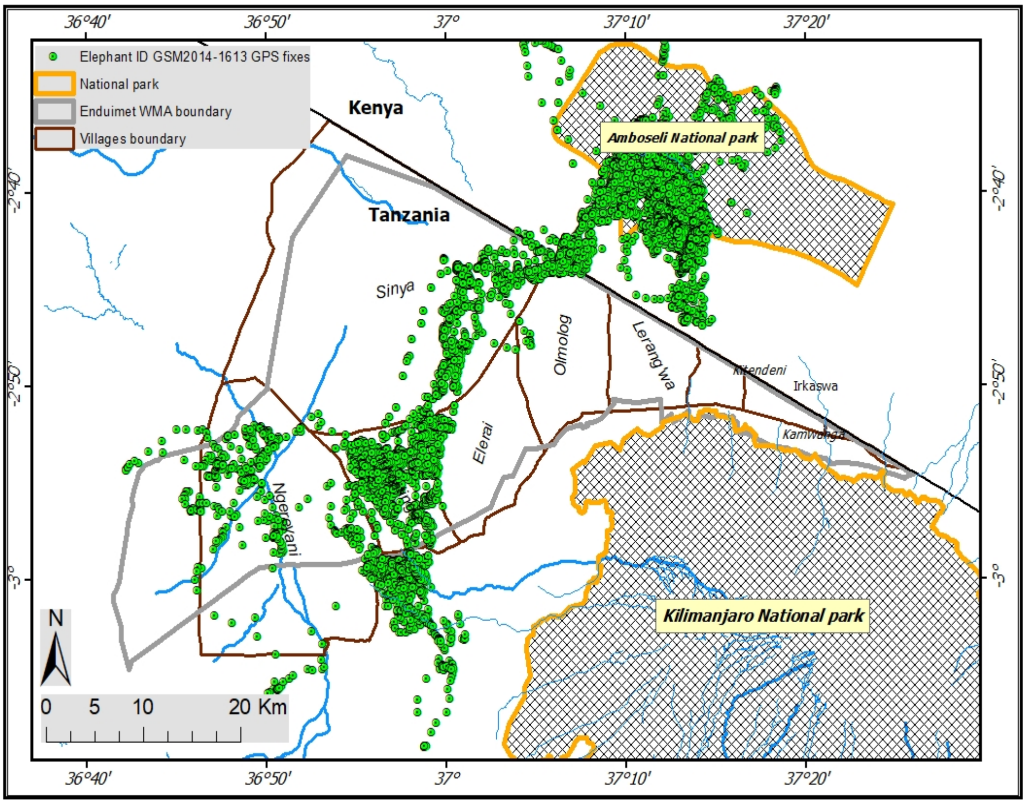

Figure A2. Spatial distribution of one collared elephant with the ID GSM2014-1613 (n = 17,472) in the Amboseli National Park in Kenya, in the Kilimanjaro National Park and Enduimet Wildlife Management Area (EWMA) in Tanzania. Source: Amboseli Trust for Elephants.

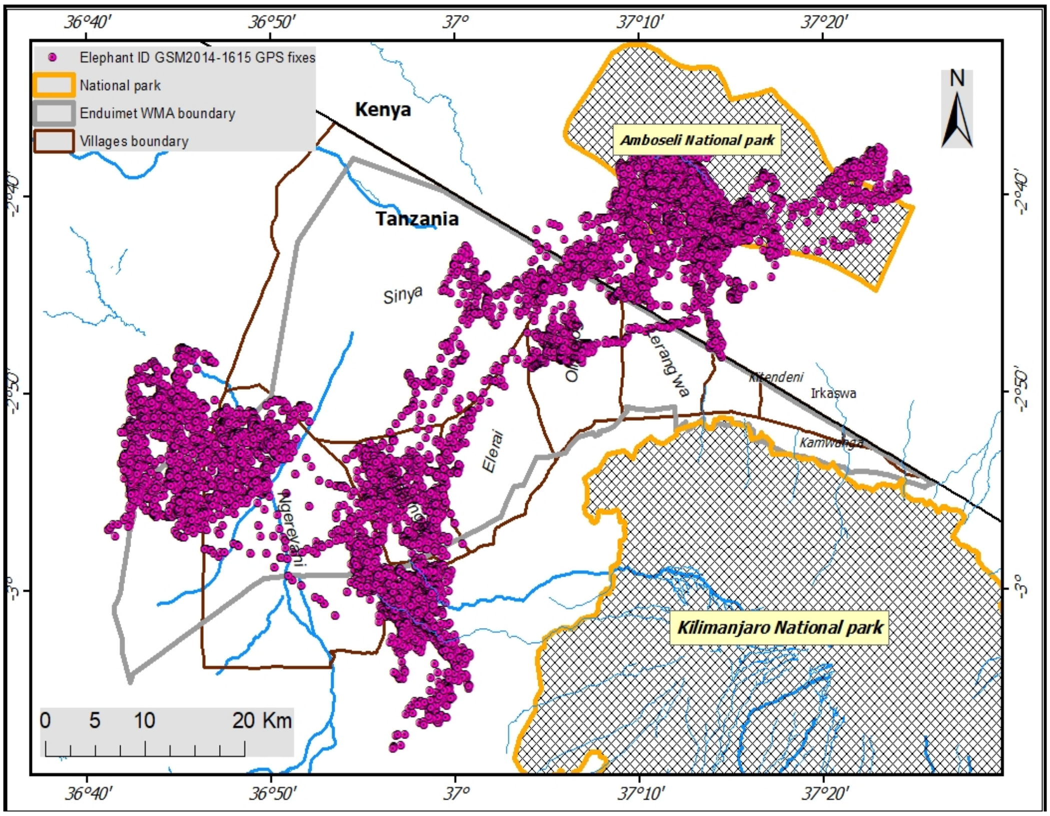

Figure A3. Spatial distribution of one collared elephant with the ID GSM2014-1615 (n = 17,472) in the Amboseli National Park in Kenya, covering the Kilimanjaro National Park and Enduimet Wildlife Management Area (EWMA) in Tanzania. Source: Amboseli Trust for Elephants.

Table A3. Annual and seasonal 100% maximum convex polygon (100% MCP), and Seasonal 95% Fixed kernel density (KDE) home range sizes (km^2) for three male elephants monitored via GPS collars in Amboseli, Kenya, and in northern Tanzania from (2019–2020). Wet = wet season (January–May; dry = dry season (June–November).

100 % MCP	Sex	No	Annual	Wet	Dry
	Male	1	552	368	368
		2	1278	1066	704
		3	819	816	169
		Mean ($\bar{x}$)	**996**	**756**	**644**
				Season	
95% KDE		**No**		**Wet**	**Dry**
	Male	1		981	700
		2		816	269
		3		568	472
		Mean ($\bar{x}$)		**740**	**466**

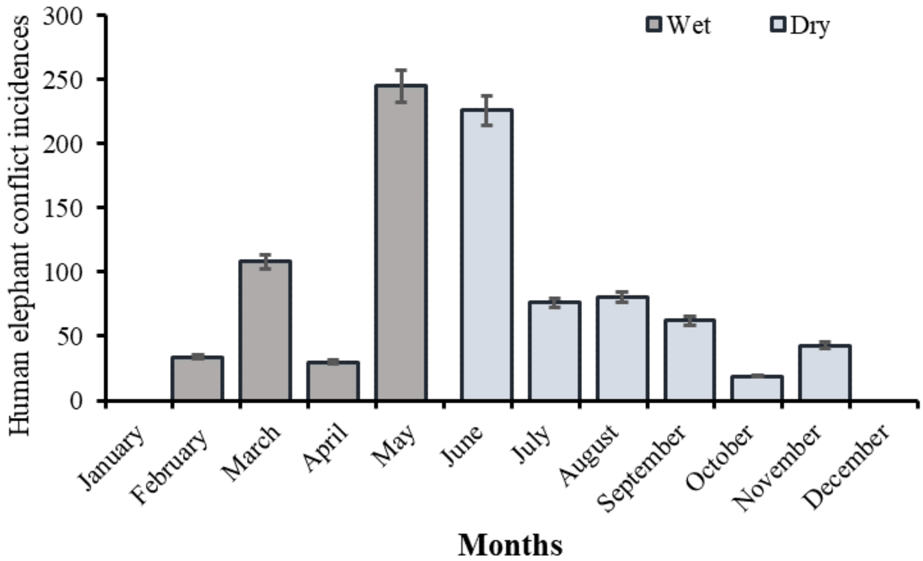

Figure A4. Temporal distribution of average (±SE) human elephant conflict (HEC) incidences reported in the Enduimet Wildlife Management Area across the year, averaged for the years 2016 and 2019. (Note: no data were collected in the months Dec and Jan, likely indicating no HEC occurrence).

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