Wildlife corridor degradation and human-wildlife conflict: a case study from Tanzania

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Abstract

In many African countries, anthropogenic pressure and poor governance have led to the degradation of wildlife corridors, which are important for the long-term viability of wildlife populations. Yet the nature of such degradation is poorly understood, hindering our ability to reverse these trends. We studied a deteriorating wildlife corridor between Katavi and Mahale National Parks in western Tanzania. Using satellite imagery, we found that the corridor still contains large areas of natural vegetation, diverse terrain and numerous water sources. There has nonetheless been increasing encroachment of the corridor by people between 1990 and 2017, exemplified by a 9% reduction in the area covered by miombo woodlands and a four-fold increase in the area covered by settlements and agricultural land. We used three additional methods to assess deterioration over the last three decades: elephants' movement routes, peoples' perception of animal populations, and incidents of human-wildlife conflicts. Elephants were primarily found only in parts of the corridor adjacent to the two national parks. Tracking of elephant spoor revealed a much-diminished corridor use, suggesting that seemingly 'healthy' habitat within a wildlife corridor will not necessarily predict the presence of elephants or perhaps of other species. Other factors, particularly the increasing presence of humans in the area, are possibly more important for predicting elephant use of a corridor. Interviews of local residents and conservation experts suggested that, although use by some animal species has declined, many ungulates were still seen in the corridor and in neighbouring villages, some of which were associated with human-wildlife conflict. All villages around the corridor were affected by human-wildlife conflict; this comprised crop damage, livestock injury or killing, and attacks on humans. We conclude that corridors could be restored if people were restricted from settling, but this would require governments to enact policies which balanced conservation of Natural Capital with survival of human populations; the latter may involve internal migration in response to growing population pressures.

KEYWORDS

Connectivity, Human-wildlife conflict, Land degradation.

1. INTRODUCTION

According to a report by the Intergovernmental Panel on Climate Change (Shukla et al., 2019), land degradation is "a negative trend in land condition, caused by direct or indirect human-induced processes, including anthropogenic climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans". In African countries such as Tanzania, poor governance, and land use change associated with increasing human activities, including agriculture, human settlements, and the development of road infrastructure, have led to rapid degradation of the ecological integrity of wildlife habitats (Caro et al., 2009, 2014;

Gandiwa et al., 2011). This has included wildlife corridors (e.g. Jones et al., 2012), with consequent isolation of protected areas, posing a threat to the long-term viability of wildlife populations (Giliba et al., 2022, 2023; Hariohay & Rø, 2015; Newmark, 2008). Yet the nature of corridor degradation, in relation to natural vegetation and other habitat features, as well as animal use, is poorly documented.

Wildlife corridors are often deemed as either 'intact' or 'cut' (Caro et al., 2009; Green et al., 2018) but this is an overly simplistic approach which overlooks much of the detail crucial for an accurate and holistic assessment, which is required for effective restoration. It can be useful to study a proxy species that represents (i.e. is closely associated with) other large mammal species with similar habitats in that particular area (Caro, 2010). Establishing an appropriate proxy species should ideally be based on site-specific evaluation. For example, the quality of the wildlife corridor between Lake Manyara and Tarangire National Parks in Tanzania, which is largely *Acacia-Commiphora* grassland ecosystem, is most accurately assessed by monitoring movements of zebra (whose presence is closely associated with large mammal species' richness in the area) within the corridor, and not by the more commonly used metric of evaluating elephant movements (Epps et al., 2011; Riggio et al., 2022). The corridor we studied here lies between Katavi and Mahale National Parks, and neighbouring areas around these parks. It was previously used by elephants, mainly during the wet season (Caro et al., 2013; Jones et al., 2009) and was historically, and is still commonly, regarded as an 'elephant corridor', even though other animals also use it: hence the focus of the current study on elephants.

A former joint vision of the Katavi and Mahale National Park authorities, and the associated local government conservation authorities, was to maintain wildlife diversity and functionality in this western Tanzanian region as part of the Greater Katavi-Mahale ecosystem. However, there has never been an evaluation of policy impact on changes in wildlife presence within that corridor over time. Using the Katavi-Mahale National Park corridor as a case study, we set out to identify the way(s) in which the value of a wildlife corridor may deteriorate. We employed a mixed methods approach, to identify elephant movement and evaluate the nature and extent of possible human-wildlife conflicts in the area. Specifically, we (1) mapped the land cover changes that have taken place in the corridor over the last three decades using remotely sensed imagery; (2) identified and evaluated current elephant movement routes using ground surveys, and (3) identified human perceptions of animal populations and reports of human-wildlife conflict in the area. We asked people about human-wildlife conflicts in order to explore what human perceptions might reveal about the functionality of the corridor. It is known that human communities are at greater risk of conflicts with wildlife when they expand agriculture, settlements and livestock keeping into wildlife corridors (Buchholtz et al., 2020) and this information can help determine corridor degradation. Such collective information has the potential to provide a basis for developing nuanced strategies to both conserve wildlife and mitigate conflict between wild animal species and humans.

2. METHODS

2.1. Study Area

The Katavi-Mahale wildlife corridor, which is not yet legally designated, and therefore has no agency officially managing it, stretches for about 100 km across Katavi and Kigoma administrative regions, and forms part of an extensive and largely unprotected area between the Katavi and Mahale National Parks (Figure 1) (Giliba et al., 2022; Thomsen et al., 2023). The boundary of the study area was chosen based on the knowledge and experience of wildlife experts and local people on the distribution and movements of wild animals in this area. The habitat of the corridor is woodland, mainly characterized by *Brachystegia, Acacia, Combretum, Commifora, Grewia, Kigelia, Pterocarpus* and *Terminalia* species, with vegetation gradients of closed forest, dense thickets, and open understory in parts that are regularly burned (Caro et al., 2009; Carvalho et al., 2022). Some areas of the unprotected land formerly had exceptionally high value for biodiversity and conservation, providing important habitat for both endangered African elephant *(Loxodonta africana)* and eastern chimpanzee (*Pan troglodytes schweinfurthi)* populations, especially in the relatively densely forested hills (e.g., the Wansisi Hills) and associated valleys (Piel & Stewart, 2014). Farming, livestock keeping, and fishing constitute the main livelihood activities of the human communities in and around the wildlife corridor.

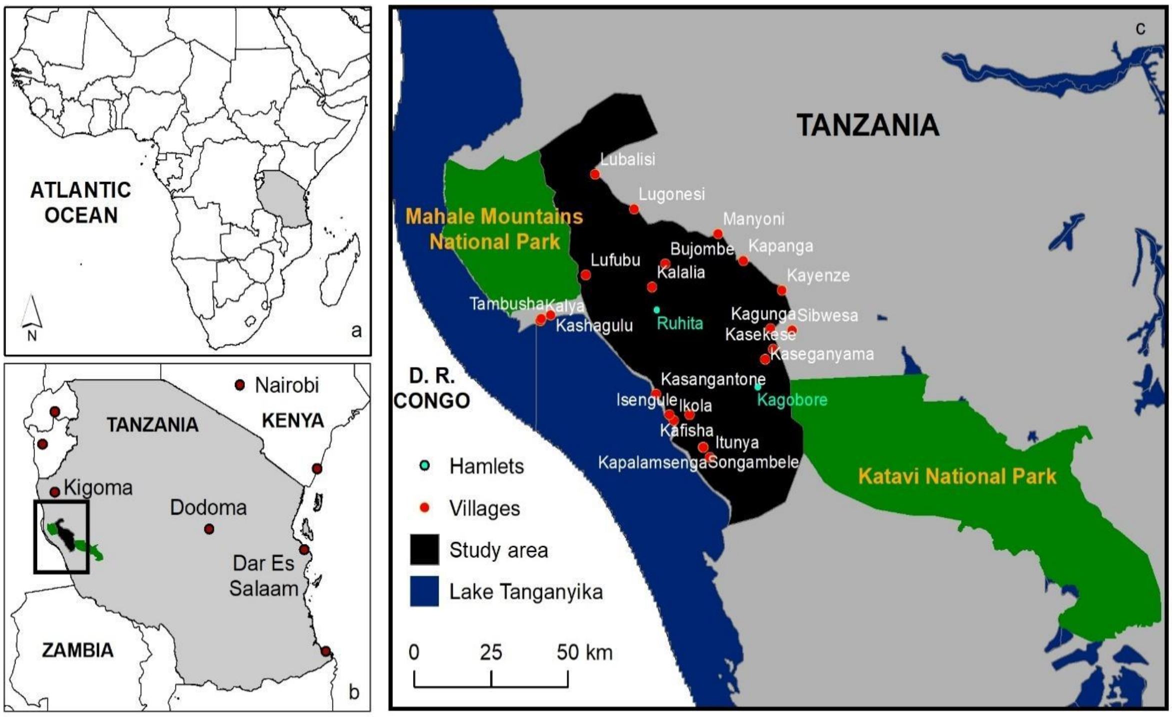

Figure 1. The study area within (a) Africa and (b) Tanzania. Its location with respect to the Mahale Mountains and Katavi National Parks is shown in (c). The 19 villages that were visited are: Kafisha, Kagunga, Itunya, Kapalamsenga, Songambele, Sibwesa, Kasekese, Shukula, Kaseganyama, Isengule, Kasangantongwe, Kalalia, Kalya, Kapanga, Lubalisi, Bujombe, Ikola, Lugonesi, and Tambusha.

2.2. Land cover change mapping

Land cover was mapped using the Tier 1 Landsat archive on Google Earth Engine (GEE) (Gorelick et al., 2017) in two epochs centred around the years 1990 and 2017. The choice of the two epochs was determined by the availability of Landsat imagery for the study area (which extends over four Landsat scenes) and the timing of the high-resolution images used for the sampling and validation: 1990 is the earliest date available of cloud free data while 2017 is the date that most closely matches the acquisition of the high resolution images. Nine spectral-temporal metrics were calculated from all available dry season data (1st July to 31st October) within a 5-year period (1988-1992 for the first epoch and 2015-2019 for the second): for each Landsat band, the mean, median, minimum, maximum, standard deviation and the 5th, 25th, 75th and 95th percentiles were determined (Higginbottom et al., 2018; Mueller et al., 2015; Symeonakis et al., 2018). We then classified these images, which consisted of 54 bands each (6 Landsat bands × 9 metrics), using the unsupervised ISODATA classification algorithm in ERDAS Imagine 2018, with the following parameters: 40 classes, 99 maximum iterations, and 0.95 convergence threshold. The 40 output classes were then grouped to form the desired five main land use/cover classes of the study area: miombo woodland, managed land (settlements and farming), bamboo forest, grassland and riverine vegetation. These classes were chosen based on our knowledge of the area (i.e., through communication with local residents and our own ground surveys and experience), their spectral separability at the Landsat spectral and spatial resolution, and the results of other studies in the region (McLester et al., 2019; Silangwa, 2016; Simonetti et al., 2014).

An accuracy assessment of the classified map of the recent epoch (i.e. 2017) was undertaken using the high resolution 'basemap' imagery within ArcGIS 10.8 software, to evaluate its quality by assessing errors of commission and omission (Congalton, 2001). A total of 3,112 validation points were taken in a stratified random sampling approach. For the first epoch (i.e. 1990), TimeSync-Plus v4.6 was used (Cohen et al., 2010) to check for unchanged pixels at the sample locations of the recent epoch. This resulted in 2,219 samples, for which we could confidently conclude that no change in the Landsat time series occurred. A post classification comparison was employed to quantify land cover change within the study period (Nababa et al., 2020).

2.3. Focus groups and individual interviews

Focus groups and face-to face interviews with local villagers were used to gather information on their knowledge of use of the corridor by elephants and other wildlife species, and on the history and perception of human-elephant conflict. Nineteen villages were selected from both the Katavi and Kigoma regions, but with priority given to villages that bordered the corridor (Figure 1). Most villages were located in the Katavi region, as this is where the majority of the corridor is located. Basic socio-economic and ecological information (human and livestock population, main livelihood activities, common ethnic groups, status of land use planning, main source of water, wildlife species present in the corridor, conservation strategies for the wildlife corridor, and elephant usage of the corridor) on each village was collected from village executive officers and via official reports from district councils and conservation institutions. The ground survey data are provided as Supplementary Material.

Two focus group meetings were conducted in each village. Village executive officers and village chairpersons facilitated recruitment of the participants, organised the meetings (which took place in October and November 2018), and also participated in the focus groups. One of the focus group meetings was held with villagers with specific knowledge of the history of the village and the surrounding areas. Participants in these groups were selected to ensure a balanced representation of gender, age (elders, middle-aged and young people) and socio-economic groups (mainly pastoralists and farmers) but it is important to note that members had been selected by village officials. The other focus group comprised village leaders (members of village councils, land or environmental committees) and other government officials working at the village/ward-level, such as extension officers, livestock officers and social development officers, which again was not a random selection. A total of 207 (mean 7±3) people in 38 focus groups participated in the village focus group discussions. Focus group discussions were carefully moderated to ensure all voices were heard. Typically, each focus group discussion lasted for approximately one hour. Group conversations were recorded in notebooks in Swahili and later translated to English by the first author (ME).

Focus group meetings were supplemented with face-to-face interviews (each lasting between 20 to 30 minutes) with 11 users (bus drivers and conductors) of the Ikola-Mpanda public road (a road that crosses the corridor for a distance of about 25 km), and with conservation experts (8 district natural management officials in the Katavi [Tanganyika district council] and Kigoma [Uvinza district council] regions, and six staff members from Katavi and Mahale National Parks). We also reviewed official reports from relevant conservation institutions and local governments (Tanganyika and Uvinza district councils) to obtain socio-economic information on the area and ecological information on the past and present status of the elephant corridor.

At each focus group meeting and interview, the first author and the research assistants introduced themselves and the purpose of the study. To obtain prior informed consent of participants, the project team explained the participant's role, the extent to which anonymity and confidentiality would be maintained, and how the data would be used and stored. Explanation (both verbal and written) was given in Swahili, which all participants could speak and understand, and most were also able to read and write. Relevant information was collected using a 'topic guide' designed to facilitate the focus group discussion and face-to-face interviews. Visual aids such as maps of the ecosystem, wildlife corridors, and pictures of various wild animal species were used for the purpose of clear identification and clarification of information during the discussion.

Face-to-face interviews and focus groups are qualitative research methods (Bryman, 2016). They are designed to understand participants' interpretation of the world. Face-to-face interviews and the carefully moderated interactive focus group forum can elicit rich in-depth, nuanced data to understand participants' perspectives, attitudes, beliefs and an understanding of their experiences. However, while perspectives of purposively selected interviewees and focus group members may be indicative of wider views, they cannot be generalised, nor quantified and ranked (Gerger Swartling, 2007).

2.4. **Tracking and mapping**

A survey team, which included two experienced local guides, carried out ground tracking of elephant routes throughout the corridor at the onset of the wet season, during which time the corridor was still accessible and there was a likelihood of observing elephants. Selection of the sites for tracking was based on elephant movement information obtained from residents of surrounding villages (through focus group discussions), and with advice from experienced local guides who were familiar with such routes and were subsequently involved in tracking of the routes.

The field team walked the entire elephant migratory route (~100 km) over 32 consecutive days during the onset of the wet season in November and December 2018. The time taken to compete the route was dictated by the challenging nature of the terrain, the prevailingly rainy weather conditions, and the local availability of overnight accommodation for the survey team. During tracking of the migratory route, efforts were made to minimise noise, to avoid any disturbance to elephants and other wild animals. The team tracked only the main routes; this was judged sufficient, as several of the smaller side routes later joined the main routes. The team followed the main elephants' movement routes and determined location coordinates using a hand-held GPS unit. Recorded data included GPS location, habitat type (e.g. woodland, grassland), and signs of the presence of elephants and other wild animals (e.g., footprints, dung). The type of vegetation was noted because wild animals (including elephants) can be attracted to particular vegetation or its fruits, such as palms (e.g., *Borassus* palm; *Borassus aethiopum*) and Marula tree (*Scelerocaria birrea*).

3. **RESULTS**

3.1. **Land cover and land cover change**

Land cover mapping results show miombo woodland was by far the largest land cover class, occupying more than 70% of the total area at both the start and end dates of the study period (Figure

2; Table 1). This region experienced a net loss of this woodland type of almost 9% between 1990 and 2017 (351 km²; Table 1). Grassland and riverine vegetation were also reduced, with a net recorded loss of 18% and 31%, respectively. Human settlements and farmland saw a substantial increase, quadrupling in size from 1990 to 2017 (Table 1). The area covered by bamboo forests also substantially increased between the two dates, especially in the area in the northwest on the border with Mahale National Park.

Table 1. Land cover area statistics and change in the area covered by each type between the two periods of study.

Land cover	**1990**	**2017**	**Change (2017 – 1990)**	
	Area (km²)		**Area** (km²)	**%**
Miombo Woodland	4049	3698	-351	-9
Managed (Settlements & Farmland)	137	523	386	282
Bamboo Forest	110	264	154	140
Grassland	727	596	-131	-18
Riverine Vegetation	187	128	-59	-31

The classification results produced high overall accuracies of 79% (95% CI: ±2%) and 80% (95% CI: ±3%) for the two epochs, respectively (Supporting Information S1 and S2). Per-class accuracies (% correct, producer's and user's Accuracies; Tables S1, S2) were also high, with the exception of the grassland class. The lower accuracy for this type was due to spectral confusion with riverine vegetation, as a large number of grassland pixels were omitted from this class and committed to the riverine vegetation in both dates (Tables S1 and S2).

The two land cover maps in Figure 2 were used to calculate the contingency matrix in Table 2. The matrix summarises, for the period of study, the area that has remained unchanged, and (where relevant) the area and the type of change observed for each individual class. It also provides a summary of the area covered by each class in 1990 and in 2017 as well as of the gains and losses they experienced. The spatial distribution of the latter is also illustrated in Figures 3a - 3f for three of the classes: miombo woodland, managed land and grassland.

Table 2. Contingency matrix for the period of study representing stable (in bold) and changed areas in km²

		Area covered by each class, 2017 (km²)						
		Miombo	**Managed**	**Bamboo**	**Grass**	**Riverine**	**1990 Total**	**Gross loss**
Area covered by each class, 1990 (km²)	**Miombo**	**2987**	387	211	439	25	4049	1062
	Managed	71	**37**	3	26	0	137	100
	Bamboo	67	17	**10**	16	0	110	100
	Grass	492	81	40	**113**	0	727	614
	Riverine	80	1	1	2	**103**	187	84
	2017 Total	3698	523	264	596	128		
	Gross gain	711	486	254	483	25		

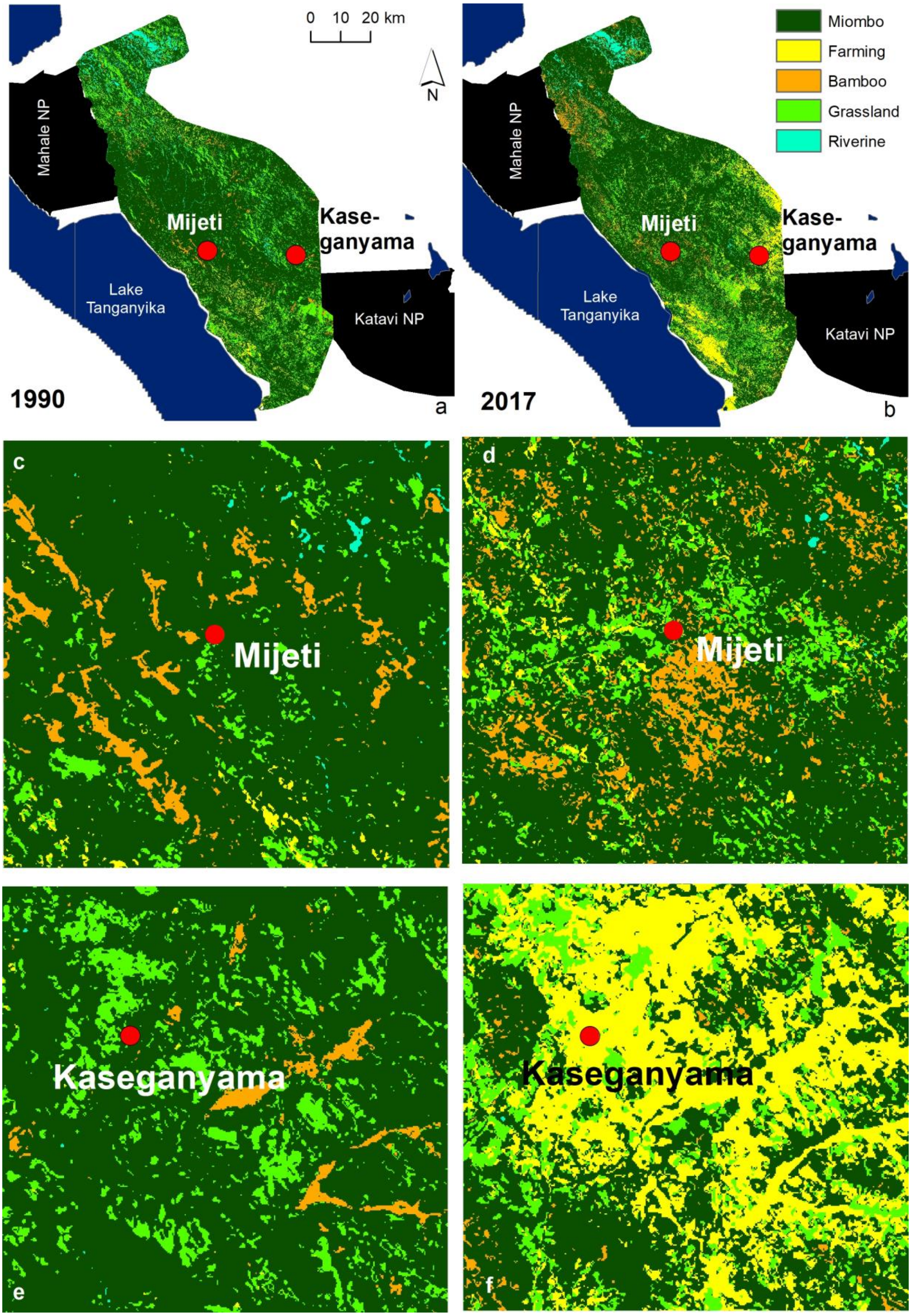

Figure 2. Land use/cover maps of the study area for (a) 1990 and (b) 2017. Managed land use includes settlements and farmland. NP: National Park. (c) (d) (e) and (f) are zoom-ins in the area around Mijeti and Kaseganyama village.

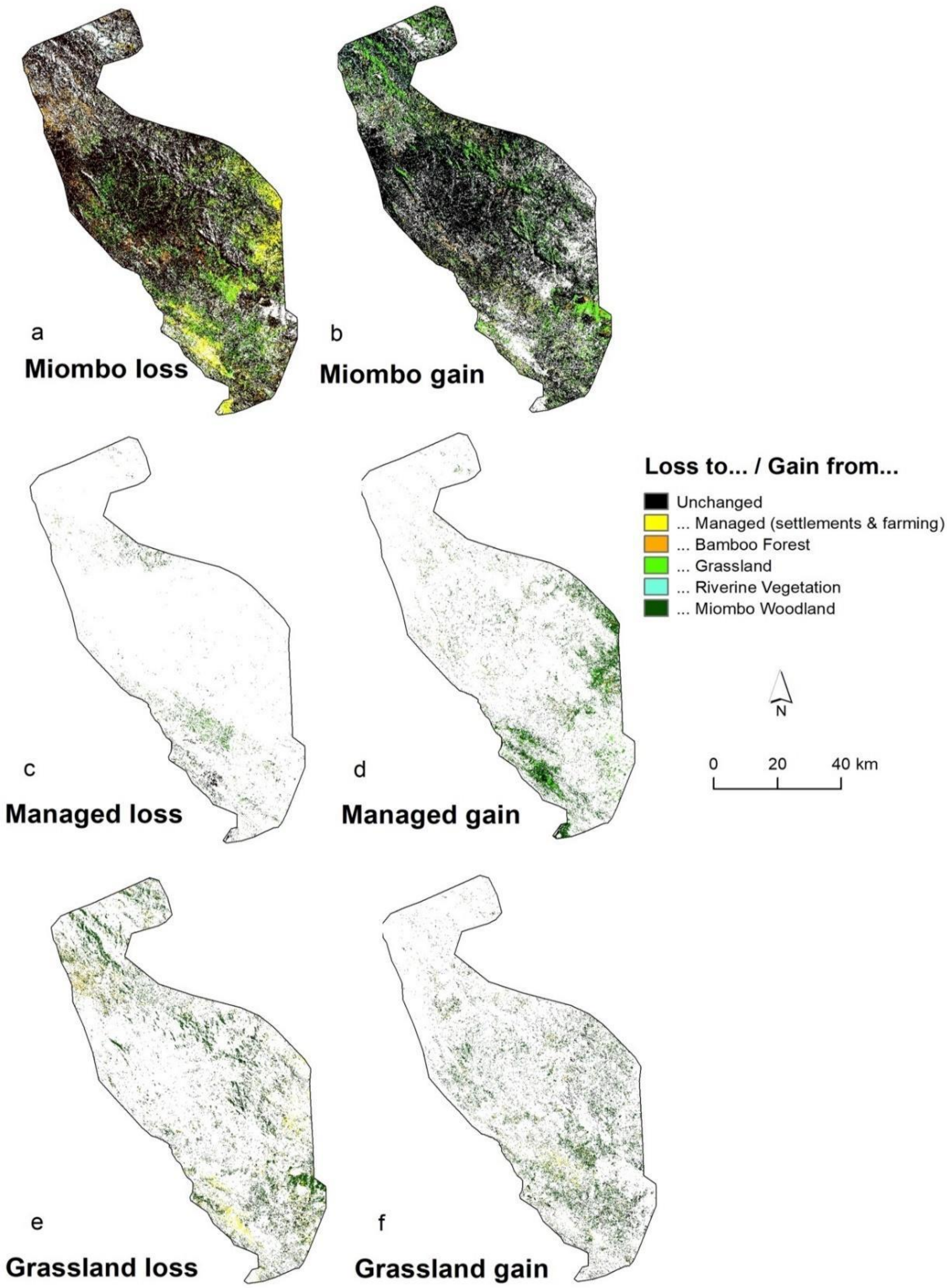

Figure 3. Land cover losses and gains. Losses and gains of three land cover types between 1990 and 2017: (a) Miombo Woodland loss; (b) Miombo Woodland gains; (c) Settlements & farmland loss; (d) Settlements & farmland gains; (e) Grassland loss; (f) Grassland gain.

3.2. **Focus groups and interviews**

The following subsections present key findings that emerged from the focus groups and individual face-to-face interviews.

3.2.1. **Historic and current wildlife use of the corridor**

Participants in the focus groups and interviewees recalled frequently sighting herds of up to 50 elephants moving through the corridor during the 1980s and 1990s: (1) from Katavi National Park to Mahale National Park (Figure 4a), particularly during the wet season (November to April), and (2) back to Katavi National Park in the early dry season (May and July). More specifically, elephants frequently used to move along a migratory route that passed through Nkamba forest reserve, Lyamungoroka and Kagobore/Kaseganyama areas, then to Wamweru, and from there to either Mijeti via Iganikilo mbuga or to Wansisi Hills/Wamweru plains, then to Manda, Misanga, and Ruhita areas, before reaching Mnyamasi, which also connects to Mijeti. From there, the elephant migratory route proceeded to Kankosha, Bugalaba, Lufubu and then to Mahale National Park in Kigoma (Figure 4a). According to the focus group participants, in the past (until the 1990s), elephants also frequently moved between the parks via an additional route extending further northeast from Mahale National Park to Ntakata and Tongwe forest reserves before arriving at Katavi National Park. According to focus group participants in Lubalisi and Lugonesi villages (which are located around Ntakata and Tongwe forest reserves), elephants used to migrate freely and frequently between these areas, as observed from 1962 to the late 1990s. During this time, elephants used to move from Mahale National Park via Kakungu hill, River Silafu, Lungwa, Mankasa, Lutagano hill between Lubalisi and Ikuburu villages and then to Ntakata forests, and from there they proceeded to Katavi National Park through Tongwe west forest reserve, via Manyoni and Bujombe areas, Wasinsi Hills and then to Lyamungoroka areas before finally moving into Katavi National Park (Figure 4b).

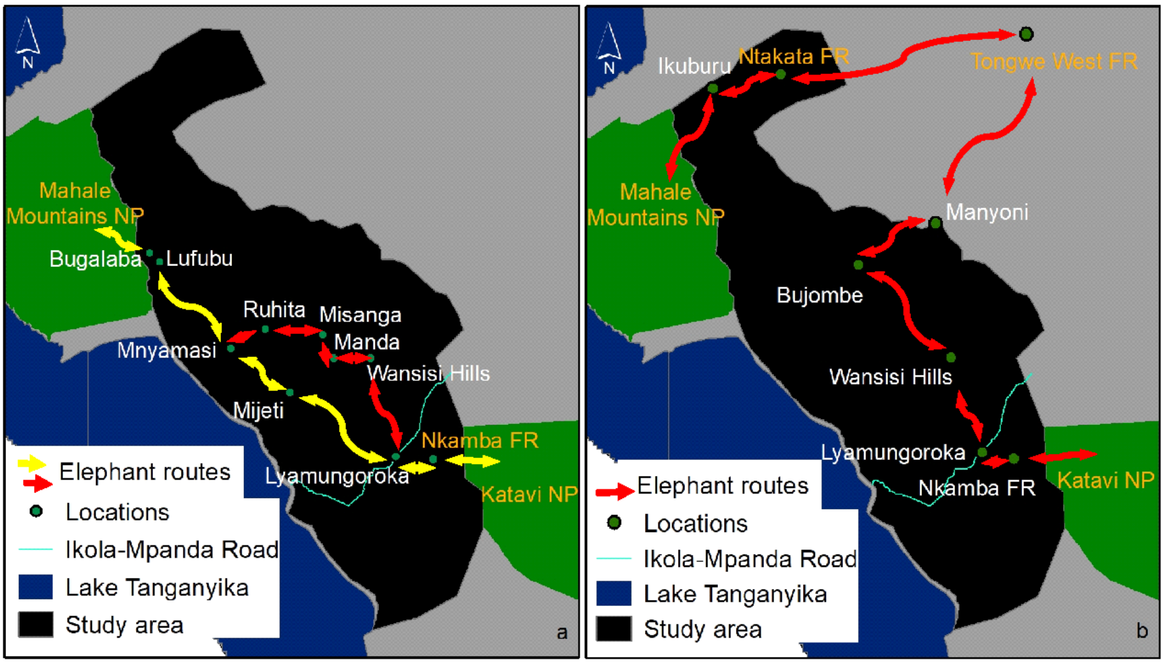

Figure 4. Elephant migratory routes. Historical common elephant migratory routes (a), and northern elephant migratory route (b) between Katavi and Mahale Mountains National Parks, according to local inhabitants' reports. Red and yellow arrows indicate different routes used.

Members of the focus groups and interviewees reported observing elephants searching for fruits from borassus palms and marula trees and feeding on bamboo. Participants reported elephants apparently searching for suitable habitat and environmental conditions, such as the forested hills around Mahale National Park, where they tend to stay in the wet season. They also indicated that Mahale National Park, and the neighbouring areas, such as Ntakata forest, were frequently used as breeding sites by the elephants. Participants further reported that they believed that elephant populations in the corridor, and their frequency of corridor use, had declined substantially over the past 20 years such that, in recent years, relatively few elephants (on average 5-10 individuals per herd) were sighted, in contrast to the herds of up to 50 individuals that were commonly sighted in the past. However, as in the past, recent sightings occurred mainly during the wet season, especially between 2016 and 2018.

The focus groups and individual interviews revealed that many other wild animal species had historically been, and, importantly, were still using all or parts of the Katavi-Mahale corridor (Table 3). Focus groups in each village mentioned a number of wildlife species that reportedly raided, or were sighted, in the villages, and which most likely utilised the corridor (Table 3). Most of the chimpanzees resided primarily in the remaining forested ranges of Wansisi Hills (Figure 4) that stretched along the eastern border of the corridor, including parts of Kagunga village, Manda area and Bujombe Hills. As was the case with elephants, all these species were often sighted in the corridor during the wet season (though there were some cases in dry season) and often tended to occur in the same areas that were preferred by elephants.

Table 3. Wild animal species reported in the villages around the corridor

Species common name	Scientific name	Species common name	Scientific name
Yellow baboon	*Papio cynocephalu*	Rabbit	*Oryctolagus cuniculus*
Spotted hyena	*Crocuta crocuta*	Zebra	*Equus quagga*
Vervet monkey	*Chlorocebus pygerythrus*	Dikdik	*Madoqua kirkii*
Bushbuck	*Tragelaphus scriptus*	Porcupine	*Hystrix cristata*
Common bushpig	*Potamochoerus larvatus*	Black backed jackal	*Canis mesomelas*
Hippopotamus	*Hippopotamus amphibius*	Honey badger	*Mellivora capensis*
Elephant	*Loxodonta africana*	Greater kudu	*Tragelaphus strepsiceros*
Lion	*Panthera leo*	Topi	*Damaliscus lunatus*
Common duiker	*Sylvicapra grimmia*	Warthog	*Phacochoerus africanus*
Nile crocodile	*Crocodylus niloticus*	Pangolin	*Smutsia temmincki*
Chimpanzee	*Pan troglodytes schweinfurthi*	Wild dog	*Lycaon pictus*
African buffalo	*Syncerus caffer*	Eland	*Taurotragus oryx*
Roan antelope	*Hippotragus equinus*	Giraffe	*Giraffa camelopardalis*
Hartebeest	*Alcelaphus buselaphus*	Impala	*Aepyceros melampus*
Leopard	*Panthera pardus*	Sable antelope	*Hippotragus niger*
Waterbuck	*Kobus ellipsiprymnus*		

3.2.2. **Human-wildlife conflict and social-economic issues**

None of the villages were perceived by focus group participants and interviewees to be free from human-wildlife conflict. Such conflicts comprised crop damage (especially to maize, cassava, rice and beans), livestock injury or killing (e.g., attacks on cattle, sheep and goats) and attacks on humans. Although not a statistically representative sample, participants' perceptions were that the spotted hyena was the species of wildlife that most frequently attacked livestock. Yellow baboons, bushpigs, and vervet monkeys (Table 3) were the three wild animals that most commonly damaged crops. Elephants were among the top five wild animal species perceived as being most commonly involved in crop damage, especially in villages near the parks. Other species included hippopotami, lions, leopards and crocodiles (Table 3) which were reportedly involved in human attacks or threatening human life.

The most widely employed (and generally accepted as effective) strategy to protect crop farms against damage by wild animals was by physically guarding them (i.e. by human presence), during both day and night. This was often carried out in combination with other tools and techniques, such as setting fires and erecting scarecrows inside, or at the boundary of, crop fields. Another key strategy employed to protect livestock (especially goats and sheep) was to keep them in strong bomas (traditionally fenced/walled livestock enclosures) that are not easily penetrable, particularly by spotted hyenas (Table 3), the most problematic predator.

Focus group participants and interviewees also identified several human-wildlife conflict control strategies that they thought would be helpful in their villages, provided that they were effectively adopted and supported by the government. Three commonly proposed strategies were: (i) Putting in place rapid response mechanisms, including permanently stationing armed game rangers in the villages. However, villages proposing this solution reported that, at present, they lack a game ranger who would respond promptly in assisting with human-wildlife conflicts; (ii) Providing education, training, and equipment to villagers, or village game scouts, to enable an effective local response to problem animals in the villages; (iii) Erecting electric fences around the farms or wildlife protected areas to prevent movement of problem animals into the farms and settlement areas.

All villages reported an increase in human and livestock populations over time, but the extent of this increase varied across the villages (Supporting Information S3). According to participants (focus groups and individual interviewees), the number of internal migrants (mainly agro-pastoralists) in most of the villages had already surpassed the number of native residents, whose main livelihood was farming.

3.3. Tracking and mapping

Ground tracking in the Katavi-Mahale corridor suggested that elephants now rarely use those parts of the corridor located furthest away from the two national parks. No elephants were sighted during this assessment, only signs of their presence (tracks/footprints, dung and old migratory routes) were detected. Many fresh signs of elephant presence were observed close to (30 km) the two national parks, such as Nkamba and Lyamungoroka areas (around Katavi National Park), and Lufubu (around Mahale National Park) (Supporting Information S4). However, during tracking we noticed (directly or by signs such as footprints and scats) the presence of several other mammalian species, including roan antelope, sable antelope, bushbuck, bush pig, warthog, yellow baboon, vervet monkey, common duiker, African buffalo, greater kudu, spotted hyena, and chimpanzee. These wildlife species were relatively widespread in different parts of the corridor.

4. DISCUSSION

4.1. General

Wildlife conservation ecologists face the problem that increasingly crowded agricultural landscapes generate increasing human-wildlife-conflict (Amwata et al., 2006; Walpole et al., 2006). One solution is to confine wildlife to protected areas, which may be connected by corridors (e.g. Ghoddousi et al., 2020; Giliba et al., 2023; Neelakantan et al., 2019). However, the Katavi-Mahale wildlife corridor, which is not currently legally designated, is being rapidly encroached by a growing human population engaged in farming, livestock keeping and the establishment of settlements. For instance, we found that land under farming and settlement quadrupled between 1990 and 2017, while miombo woodland, riverine forests and grassland all declined. Another study of the Greater Mahale ecosystem (part of which contained the Katavi-Mahale corridor) similarly showed that suitable habitats for elephants declined by more than 50% between 2008 and 2020 (Thomsen et al., 2023).

While elephants are known to be highly adaptable, for instance, changing their behaviours when using human-dominated landscapes (Graham et al., 2009), the evidence we collected from both interviews and ground tracking shows that their use of the Katavi-Mahale wildlife corridor has substantially declined. This apparent sensitivity to corridor degradation is in accordance with findings of another study carried out in an area between Lake Manyara and Tarangire National Parks in Tanzania (Riggio et al., 2022). However, we found that other species of large mammals were still using the degraded areas between the Katavi and Mahale National Parks.

The declining use of the corridor by elephants is most likely due to increasing human disturbance. This is also supported by another study which identified that elephant's habitat suitability in this area is more dependent on anthropogenic variables than on environmental ones (Giliba et al., 2023). In our discussions, the majority of villagers indicated they were aware of the importance of this corridor in supporting wildlife, but it is their activities that are encroaching the corridor, and most villagers likely view the decline of elephants and other animals in the corridor as positive, as this will reduce the incidence of conflict (see also Bencin et al., 2016). They even suggested that their farms and the corridor and neighbouring protected areas could be separated by fencing so that wild animals, including elephants, do not damage their properties. Furthermore, as the human population is growing, the local communities need more land, which will lead to further encroachment. Some interviewees and focus group participants suggested that the increasing human pressure was due to an influx of internal migrants from other regions of the country (see also Giliba et al., 2022; Jones et al., 2012; Walpole et al., 2006). This assertion was largely supported by both interviewees and focus group participants, regardless of whether they themselves were internal migrants or members of indigenous communities.

We have identified the ways in which the values of a wildlife corridor may deteriorate over time. In general, we discovered that land use change has impacted wildlife habitat, while not severely so at a landscape scale, it was sufficient to adversely affect one of the primary historic elephant migratory routes that once characterized Tanzania. More optimistically, wild ruminants still use the area and some sectors of society are open to living with wildlife, hence an opportunity for conserving the corridor. On the other hand, however, there is intense land pressure from internal immigrants that continues to build, and the Tanzanian Government seems unwilling to place its own wildlife concerns over human interests. We now discuss these issues in more detail.

4.2. Status of the Katavi-Mahale corridor

Information gathered from direct on-the-ground observations, and from focus groups and one-to-one interviews, indicated that a growing human population (and associated activities) has resulted in encroachment of several areas that used to serve as habitats and migratory routes for elephants moving between Katavi and Mahale National Parks. Farming, human settlements and livestock keeping has been largely associated with deforestation and was scattered throughout the corridor and along many parts of the migratory routes, with a high concentration particularly in mid-sections of the route between Mahale and Katavi National Parks. Notably, there was an area of about 3 km^2 under active farming along the main Katavi-Mahale wildlife migratory route, and sections of key elephant areas (i.e., those areas frequently used by elephants as identified by the focus groups and interviews and confirmed by ground truthing) such as Mijeti, Manda, Bugalaba and the foot of the Wansisi Hills, which had already been encroached by farming activities (Figure Supplementary Material S4). Often the existing farmland was associated with settlements, most of which consisted of traditional wooden and thatched-roof houses, and a small number of brick-built houses.

These changes have been associated with a substantial decline in wildlife populations, and in the frequency with which wildlife use the corridor, over the last 20 years, particularly elephants. Several interviewees expressed the opinion that poaching did not occur frequently and was thus unlikely to be a major factor in the decline of wildlife populations. According to them, it was the presence of farming and livestock in wildlife areas that had led to a decrease in wild herbivore (including elephant) abundance and use of the corridor (Ahmed et al., 2012; de Leeuw et al., 2001; Giliba et al., 2023; Stephens et al., 2001). The decline in elephants' use of the corridor is unlikely to be due to decline in the overall elephant population, as the wildlife census by Tanzania Wildlife Research Institute (TAWIRI) in Katavi-Rukwa ecosystem (Caro, 2016; TAWIRI, 2022) and ecological monitoring and observations by park managers (first author's personal communication with park ecologists) in both Katavi and Mahale National Parks, all suggest that elephants populations are stable.

Focus groups in most of the surveyed villages reported that the current human-wildlife conflict was infrequent compared with previous years, especially prior to the last 15-20 years, when there were lower human populations and a more abundant and diverse wildlife. Further, all groups consulted (wildlife professionals, bus drivers/conductors and community members) consistently reported a decline in wild animals in the corridor. For instance, elephant numbers, frequency of corridor use, and incidence of human-elephant conflicts were all viewed as having declined (when comparing recent years to 20 years ago). While threats to humans from elephants within the corridor have decreased, elephants, particularly males, are nevertheless likely to have high activity around national park boundaries (which primarily fall outside of the corridor), where they can have access to palatable and nutritious crops growing in adjacent fields (Gaynor et al., 2018; Hoare, 2000). Female-led elephant family groups are also involved in raiding crops, as they need to ensure that the nutritional requirements of growing calves are satisfied (Hoare, 2015). Most of the villagers thus remained vigilant in guarding their properties against damage by both elephants and other wild animals. This finding is also in agreement with other studies (see also Amwata et al., 2006; Eniang et al., 2011; Gandiwa et al., 2013; Sitati et al., 2005) which identified guarding as one of the effective mitigation strategies against crop raiding by the African elephants and other species in the savannah environment. However, guarding is a dangerous task for the people involved and should therefore always be combined with other measures such as using chilli (planted chilli as a buffer crop, chilli grease fences or burning of chilli briquettes), placement of beehive fences, or the erection of fences, which have been shown to be partially effective (Amwata et al., 2006; Kiffner et al., 2021; Walpole et al., 2006). Furthermore, some of the villagers kept their livestock in strong traditional bomas (enclosures) to protect them against attacks by problematic animals, especially spotted hyena. This finding aligns well with a study in northern Tanzania which identified spotted hyena as the most problematic animals in livestock depredation, and that fortified enclosures/bomas are a cost-effective way to mitigate livestock depredation (Kissui et al., 2019).

While the villagers in the current study expended a substantial amount of effort in protecting their properties, this was only partially effective and, in the opinion of focus group participants and interviewees, this was due to insufficient support provided by the Tanzanian Government. Such support might include stationing around-the-clock armed game rangers to protect villagers and their properties against wild animals. In addition, villagers pointed to the need for capacity building, including education and training of village residents and strengthening village institutions, to enable effective responses to human-wildlife conflict (Gandiwa et al., 2013; Hariohay & Rø, 2015; Madden, 2004; Walpole et al., 2006). Electric fencing has been shown to be effective in protecting villagers' properties against problem animals in some contexts. For instance, in Kenya and Bhutan, electric fencing technology has demonstrated the potential to reduce human-wildlife conflict and thus contribute to peaceful coexistence (Feuerbacher et al., 2021; Morang'a et al., 2023). To be effective, electric fences depend on a number of conditions such as proper maintenance, reliable infrastructure for provision of power, which is not always met in some rural contexts, and hence they do not always provide effective mitigation against problematic animals, as shown in southern Kenya (Kioko et al., 2008). Therefore, electric fencing in this poor area of Tanzania with little access to the electrical grid seems an impractical solution.

While at the time of this study, the Katavi-Mahale corridor still retained large natural areas rich in resources for wild animals' use, several areas of the corridor had already been substantially encroached by human activities, especially farming, livestock keeping and human settlements, mainly due to internal migration by agro-pastoralists (mainly the Sukuma ethnic group). Other researchers have reported a rapid human population increase in the Katavi region due to migration of these agro-pastoralists (Salerno et al., 2017). The largest increase in human population has been in the Tanganyika district, where the majority of the elephant corridor is located. Primarily as a result of this internal migration, the Katavi region (where most of the corridor is situated) recorded, in 2012, a population growth rate of 3.2%, and in 2022, 7.1% (the highest in the country), both of which were higher than the national growth rate of 2.7% and 3.2% in 2012 and 2022 respectively (United Republic of Tanzania (URT), 2022). Several participants in this study noted that this internal migration, which started in the mid-1970s, has not only led to a rapid increase in human population, but has also caused environmental degradation, especially in the form of forest clearing, landscape burning, and overgrazing in the Katavi region (Giliba et al., 2022; Salerno et al., 2014; Silangwa, 2016).

4.3. **A way forward**

In rural Africa, human-wildlife conflict mitigation measures embedded locally have received strong support from local communities and are often successful when they are part of Community Based Natural Resource Management (CBNRM) which brings communities together for a concerted effort (Salerno et al., 2021). Some of the village land-use plans around the Katavi-Mahale corridor did not sufficiently incorporate stakeholder participation and transparency of processes or decision-making (focus group participants) and lacked secure tenure, connectivity and continuity of planned land use between villages. Insufficient stakeholders' participation, and insufficient transparency of land use planning processes, contribute to lack, or poor implementation, of land use plans. Existing land use plans also lacked robust implementation strategies and consistent enforcement, which have been identified as a requirement for developing effective land use plans (Kaswamila & Songorwa, 2009). It should be noted, however, that when effectively established and managed, land use plans and community conservation are useful tools to integrate conservation and development agendas at the ecosystem and landscape levels for addressing human-wildlife conflict (Giliba et al., 2023; Hoare, 2012), and in this case for supporting the conservation of the Katavi-Mahale corridor. These tools are promoted by the current Tanzania Wildlife Conservation Act of 2009: Wildlife Conservation Regulations for Wildlife Corridors, Dispersal Areas, Buffer Zones, and Migratory Routes (United Republic of Tanzania (URT), 2018). However, to realise their full potential, further input is needed from the Tanzanian Government which, according to focus group participants and interviewees who participated in the present study, very rarely occurs (see also Amwata et al., 2006).

Whatever approaches and mechanisms are employed to protect the Katavi-Mahale corridor, they will need to be coordinated and founded in good governance at local and national levels, and will need to have the support of the affected populations, including in areas of emigration, if they are to align communities' economic needs with environmental protection (Amwata et al., 2006; Neelakantan et al., 2019; Walpole et al., 2006). As a start, we suggest that the Katavi-Mahale wildlife corridor becomes legally designated, as that would promote effective management and would be favourable for both wildlife and human communities to co-exist in the region.

ETHICAL APPROVAL

This research project received ethical approval from the University of Nottingham School of Veterinary Medicine and Science via their Science and Ethics Committee (approval no. 2425 180716). Authors did not have access to information that could identify individual participants during or after data collection.

AUTHOR CONTRIBUTIONS

Manase Elisa: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing; **Tim Caro:** Conceptualization, Investigation, Methodology, Supervision, Writing - original draft, Writing - review & editing; **Lisa Yon:** Conceptualization, Investigation, Methodology, Supervision, Writing - original draft, Writing - review & editing; **Ian Hardy:** Conceptualization, Investigation, Methodology, Supervision, Writing - original draft, Writing - review & editing; **Simon Roberts:** Conceptualization, Investigation, Methodology, Supervision, Writing - original draft, Writing - review & editing; **Elias Symeonakis:** Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing.

ACKNOWLEDGEMENTS

We would like to thank the Tanganyika District Commissioner, the management of Katavi and Mahale National Parks, and the Tanganyika and Uvinza District Executive Directors for their support. We would also like to thank the field team, especially the local guides and rangers, the conservation experts in Katavi and Kigoma regions, village chairpersons and the executive officers of the surveyed villages, and the participants of the focus group discussions and interviews for their cooperation.

This study was partially funded by the National Geographic Society (Grant WW-158C-17).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

We intend to make our data available through Open Science Framework.

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Supplementary material

Supporting Information S1

Error matrix, 1990

		Reference data					
		Miombo	**Managed**	**Bamboo**	**Grass**	**Riverine**	**Totals**
Classified Image	**Miombo**	**269**	23	13	10	17	389
	Managed	6	**316**	34	43	11	882
	Bamboo	5	47	**321**	4	23	743
	Grassland	10	8	0	**208**	58	290
	Riverine	18	11	17	98	**649**	808
	Totals	308	405	385	363	758	
Correct		87%	78%	83%	57%	86%	
Errors of commission		19%	18%	23%	23%	19%	**Total accuracy: 79%**
Errors of Omission		13%	22%	17%	43%	14%	

Supporting Information S2

Error matrix, 2017

		Reference data					
		Miombo	**Managed**	**Bamboo**	**Grass**	**Riverine**	**Totals**
Classified Image	**Miombo**	**319**	5	17	15	33	389
	Managed	12	**729**	106	9	26	882
	Bamboo	10	96	**578**	6	53	743
	Grassland	11	8	0	**210**	61	290
	Riverine	20	14	18	102	**654**	808
	Totals	372	852	719	342	827	
Correct		86%	86%	80%	61%	79%	
Errors of commission		19%	18%	23%	23%	19%	**Total accuracy: 80%**
Errors of Omission		14%	14%	20%	39%	21%	

Supporting Information S3

Human and livestock populations varied across the villages. Sibwesa village had the highest human population of almost 12,000 inhabitants, whereas Kafisha village had the smallest population size of almost 1,000 people, based on the data from the village executive officers (chief executives of the village governments). Kabungu and Sibwesa wards had the highest population growth-rate and size per ward, according to the 2012 Tanzania national census. In terms of livestock (cattle), Kalalya village in Kigoma region reported the highest number of cattle (almost 20,000), followed by Sibwesa in Katavi region which had about 10,000 cattle. However, the number of livestock reported can only serve as a general indicator of animal numbers, because, according to village executive officers, some of the livestock keepers were unwilling to report accurately the number of the cattle they owned as they were (wrongly) afraid that the government may impose charges: there are usually no mandatory government charges associated with keeping livestock. It was also difficult to confirm the accuracy of the reported numbers, as the livestock keepers frequently moved their cattle from one place to another in search of pasture and water.

Supporting information S4

Elephant route, signs of wildlife and farming

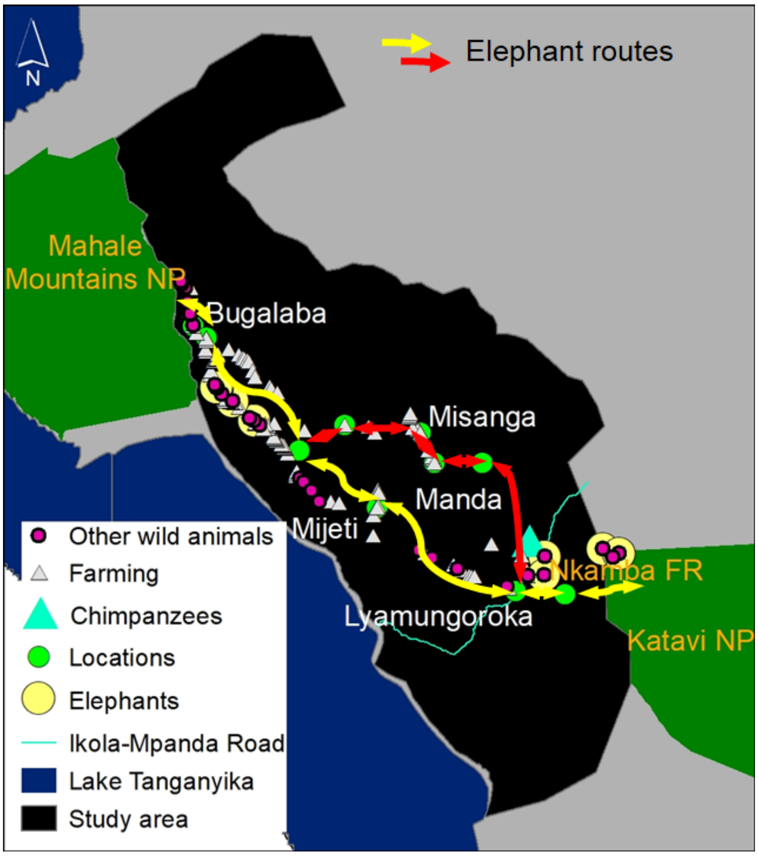

Figure S4. Elephant route, location of detected fresh signs of elephants and direct observations and signs of other wild animals, and of farming along the elephant routes in the Katavi-Mahale corridor. 'Locations' are main places/areas of interest in the corridor, as highlighted by focus group participants and/or interviewees that are also encroached by human settlements and activities.