Innovative solutions are required to halt the degradation of Africa's protected areas and achieve global conservation targets

Running Title:

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Supplementary Materials:

- **Appendix I**: Tanzanian Protected Area Types
- **Appendix II**: Large Mammal Species
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Summary

Protected areas (PAs) play an invaluable role in biodiversity conservation, but incur significant management and opportunity costs at both local and national levels. Across Africa, eco-tourism and trophy hunting are currently the most prevalent economic instruments employed to underwrite these costs. However, there is a substantial funding shortfall across Africa's PAs. This has been exacerbated by recent reductions in trophy hunting, as well as rapidly increasing opportunity costs driven by wide-scale socio-economic change. To understand the impacts of these changes, we assessed the effectiveness of different PA types at preventing forest loss in Tanzania between 2000–2018. We found that 67.5% of Tanzania's PAs are dependent on revenue from trophy hunting, and that hunting areas protect considerable geographical range for many large mammals. However, by 2018, 51% of PAs with hunting had been vacated by operators, leading to decreased management investments and losses in conservation revenue. On average, PAs suffered 3.23% forest loss, compared to 6.85% outside, and forest losses were significantly higher, and increasing more rapidly, in vacated hunting blocks. Similar trends were observed in all less-strictly protected PAs. Given the volatility of international tourism, continuing pressure on trophy hunting, and growing socio-economic demands, we highlight the need for additional economic and administrative mechanisms to achieve global conservation goals.

Keywords: Tanzania, safari hunting, trophy hunting, sport hunting, forest loss, habitat loss, protected area management, charismatic megafauna

1. Introduction

Wildlife is declining at alarming rates across the globe. More than a million species are now threatened with extinction, with a rate of species loss unprecedented in human history(IPBES, 2019). Large mammals are of particular concern, as they are especially susceptible to anthropogenic pressures such as persecution and habitat loss(Cardillo et al., 2005; Smith et al., 2018). At the same time, they often play key ecological roles as ecosystem engineers and apex predators, and their charisma attracts tourists(P. A. Lindsey et al., 2007; Ripple et al., 2016). Although Africa holds most of the world's remaining populations of large mammals, these are undergoing widespread declines and range contractions, primarily as a result of habitat loss and fragmentation, but also as a result of unsustainable hunting for meat and body parts for trade(Craigie et al., 2010a; P.A. Lindsey et al., 2017; Ogutu et al., 2016).

Protected areas (PAs) play a key role in safeguarding species from extinction by providing vital refugia for biodiversity, protecting large mammals and other taxa against the key threats of land conversion and over-exploitation(Brondizio et al., 2019). Approximately 15% of the world's terrestrial area is under some form of protection, ranging from areas wholly set aside for biodiversity to areas where natural resource extraction is permitted(UNEP-WCMC et al., 2018). However, due to a global deficit in conservation funding, many PAs are underfunded, leading to ineffective mitigation of threats to biodiversity(Peter A. Lindsey et al., 2018; Waldron et al., 2017). In addition, PAs that do not generate sufficient benefits to overcome the local or national opportunity costs of resisting land transformation – to urban, agricultural or industrial land use – may be subject to downgrading, downsizing, or degazettement(Mascia et al., 2014; Michael Norton-Griffiths & Said, 2009). There is, therefore, an urgent requirement to identify strategies to generate sufficient funding to overcome these opportunity costs and enable effective management to limit biodiversity loss.

One common mechanism for generating funding from the presence of large mammals is via trophy hunting, also known as safari or sport hunting. This approach has been used extensively across North America, Europe, Africa, Asia, and elsewhere to fund PA management while providing economic incentives to governments and landowners to prevent habitat transformation and degradation(Di Minin et al., 2016; IUCN, 2016; Peter Andrew Lindsey et al., 2012; Naidoo et al., 2016). In particular, trophy hunting is often used to generate revenue in areas unsuitable for photographic tourism due to their remoteness, low wildlife densities, and unsuitable habitat(P.A. Lindsey et al., 2006). However, if poorly managed or combined with other sources of anthropogenic mortality, trophy hunting can negatively impact the long-term survival of wildlife populations(Braczkowski et al., 2015; P.A. Lindsey et al., 2013; Loveridge et al., 2007; Packer et al., 2010). Moreover, like other forms of tourism, trophy hunting can prove socially unsustainable if the local communities in and around PAs who bear the brunt of the costs of conservation(Green et al., 2018), do not benefit sufficiently(Berkes, 2007).

In sub-Saharan Africa (SSA), where conservation is chronically underfunded(Peter A. Lindsey et al., 2018, 2014; Packer et al., 2013), there are currently few viable large scale options to generate revenue to help fund PAs, except photographic tourism and trophy hunting(P. A. Lindsey et al., 2007; Peter A. Lindsey et al., 2018). The trophy hunting industry is declining in parts of SSA(Frankfurt Zoological Society (FZS), 2018; Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2016), partly due to increasing import restrictions in the US and Europe, where there is mounting public criticism of killing animals for sport(A. Dickman et al., 2019). However, the industry remains significant, contributing approximately 200 million USD of revenue annually to African PAs and being the predominant revenue earner for over >1 million km^2 of PAs(Di Minin et al., 2016). To ensure that PAs in SSA can achieve their goals to conserve biodiversity and preserve ecosystem function, it is important to understand how different conservation models, and changes to them, may impact the long-term ecological and social sustainability of PAs. Here we explore the potential effect of these ongoing changes in PA management using examples from Tanzania.

1.1. Conservation and its funding in Tanzania

Tanzania has the largest proportion of land protected of any African country(UNEP-WCMC et al., 2018), with PAs covering approximately 48.2% of its terrestrial area(Riggio et al., 2019). This is nearly three times the Convention of Biodiversity Aichi Target 11 of 17% protection of terrestrial areas(CBD, 2010). Tanzania’s commitment to conservation means it is still one of the world’s most biodiverse countries, particularly for large mammals(Mittermeier et al., 2011) (Foley et al., 2014)(Appendix I). These include Africa’s largest remaining number of wild lions(Bauer et al., 2016). However, under scenarios of economic development and demographic change, much of Tanzania is at risk of land use change to meet growing economic demands(Tilman et al., 2017).

While PA downgrading, downsizing and degazetting (PADDD) has occurred across Africa, including recently in Tanzania(Xinhua Net, 2019), the terrestrial area of Tanzania's PAs has increased considerably in the past two decades(Riggio et al., 2019). Tanzania's PAs include strictly-protected IUCN Category II National Parks (NPs), where revenue is generated from photographic tourism, and IUCN Category IV Game Reserves (GRs), where revenue is generated through trophy hunting. These PAs (and particularly the NPs) receive by far the most effective on-the-ground protection and conservation investment(Cardillo et al., 2005; Peter A. Lindsey et al., 2018; Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2012), and we refer to them as 'strictly protected areas'. There are also various other PA types which are less-strictly protected, and where additional limited resource extraction (e.g. logging) and, in some cases, human settlement are permitted, including Game Controlled Areas (GCAs), Open Areas (OAs), Forest Reserves (FRs), and National Reserves (NRs; see Fig. 1 & Appendix I). We refer to this group as 'semi-protected' PAs.

The majority of Tanzania's PAs, in terms of both area and number, currently permit trophy hunting(Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2016) (Fig. 1) and are sub-divided into individually managed units ('hunting blocks'). Trophy hunting in Tanzania takes place within an extensive regulatory framework and entails the controlled offtake of wildlife by foreign tourists in hunting blocks leased from the government by hunting companies, under a quota system and the guidance of government-approved professional hunters(Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2016). Trophy hunting companies are expected to provide some support to management and law enforcement in the areas in which they operate. Although hunting areas contribute to conservation by forming the majority of the country's PAs, additional contributions to wildlife conservation in Tanzania, and their effectiveness compared to alternative land-use options, remains poorly studied(Booth, 2017).

In 2017, the Tanzanian government reported over US$13m in direct revenue from trophy hunting (down from a peak of US$23m in 2010), although the overall value of the industry is likely considerably higher (~US$44m in 2008)(Booth, 2010, 2017; Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2012, 2018). However, since 2014, a considerable number of hunting blocks in Tanzania have been vacated by hunting operators and returned to the government for management. Block vacancy has been attributed to many factors, including import bans of elephant and lion trophies into the United States and the EU and the resulting uncertainty faced by the hunting industry, degradation of hunting blocks, ineffective management, and policies unfavourable to long-term success (e.g. short term leases, subdivision of blocks)(Frankfurt Zoological Society (FZS), 2018; Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2016, 2018). Given the significant geographic coverage of PAs where hunting is the primary revenue generation mechanism, there is an urgent need to quantify the impact of hunting block abandonment on conservation, as this large-scale change in land tenure could have significant implications for biodiversity.

We use Tanzania as an example to determine the relative importance of different types of protected and non-protected areas for large mammals, by assessing the proportion of country range located within each type of protected and non-protected area, for 18 threatened and charismatic large mammal species. We then use forest loss as an indicator of habitat conversion (a key indicator of threat to biodiversity(Kiffner et al., 2015; Msuha et al., 2012)) to examine patterns of conversion across Tanzania, to investigate the extent and rates of forest loss within different types of protected and non-protected areas, and to identify factors likely to explain the observed patterns. Finally, we discuss the implications of our findings for land use management in Tanzania, and explore how they can help us better inform global biodiversity strategies.

2. Methods

We conducted all analyses in R(R Core Team, 2018), using the packages *tidyverse*(Wickham, 2017), *raster*(Hijmans et al., 2015), *sf*(Pebesma, 2018), and *GDAL*(Bivand et al., 2014). Area analyses based on proportion were conducted in WGS84 projection, with resolution interpreted as 30m across the study area, as a result of proximity to the equator; when the area was explicitly calculated, the Albers Equal Area projection was used.

2.1. Tanzanian Protected Area Data

We collated a database of Tanzanian PAs from a variety of sources, including the Tanzania Wildlife Research Institute(Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2016), Frankfurt Zoological Society(Frankfurt Zoological Society (FZS), 2018), and the IUCN World Database on Protected Areas(UNEP-WCMC & IUCN, 2020). These were collated and updated in early 2019 with additional information from PA managers to better reflect current land tenure on-the-ground. Data on hunting block occupancy and vacancy were obtained from an internal FZS report(Frankfurt Zoological Society (FZS), 2018), also updated in early 2019 based on information from PA managers in Tanzania. While all efforts were made to ensure this information was up to date, we acknowledge that there are some inconsistencies in the available data, particularly relating to incorrect boundaries and overlapping of different land tenure systems, and our categorisation may therefore differ slightly from other mapping efforts. Finally, changes in land tenure made after early 2019, such as the gazetting of Nyerere NP(Kimboy, 2019; Tanzania National Parks, 2019) are not reflected in our analyses, due to uncertainties regarding boundary changes at the time of publication. Wildlife Management Areas (WMAs) were excluded from all analyses, as the status of many WMAs is currently contentious or unclear, and there are substantial inconsistencies in WMA boundaries among the sources employed for this study(Bluwstein & Lund, 2018).

2.2. Large Mammal Range Data

We collated range data for medium and large mammal species (30+ kg) for Tanzania from IUCN's Red List Database(IUCN, 2019). We excluded species for which only very coarse range data were available (e.g. the entire country identified as extant range, when this is known not to be the case). This resulted in a total of 18 large mammal species, including eight species with endangered or vulnerable status on the IUCN Red List. Range maps for African wild dog (*Lycaon pictus*) and cheetah (*Acinonyx jubatus*) were updated from IUCN data based on more recent range maps published for the country(Foley et al., 2014). Lion range was based on the IUCN database(Bauer et al., 2016) and incorporating the most recent available distribution data(A. J. Dickman et al., n.d.).

For each of the 18 species, we estimated the proportion of their range within each PA type and non-PAs.

2.3. Forest Loss

We used forest loss as a proxy for natural habitat loss and conversion to agriculture, as it is strongly associated with biodiversity loss in East African systems(Kiffner et al., 2015; Msuha et al., 2012). We employed forest loss data to (i) assess the effectiveness of different PA types (including non-PAs) in protecting natural habitat from conversion, (ii) identify PAs with increasing recent annual forest loss (since 2010), (iii) identify PAs with change-points indicating large increases in annual forest loss, and (iv) compare changes in deforestation rates in active hunting blocks versus vacated hunting blocks.

2.3.1. Trends in Forest Loss

We obtained 30m resolution forest loss data from 2000 to 2018 from Global Forest Change Version 1.6(Hansen et al., 2013). We used 10% initial forest cover (in the year 2000) as a threshold for our analysis, to capture small-scale changes in forest loss(FAO, 2001). Annual forest loss data were extracted for each PA, as well as for the rest of Tanzania outside PAs. A Mann-Kendall trend test was employed to assess whether there were significant temporal trends in the proportion of forest loss both inside and outside PAs, and a paired Wilcoxon signed-rank test was used to assess whether annual rates of forest loss differed significantly inside versus outside PAs. A Mann-Kendall trend test was also used to detect the most recent increases in forest loss by detecting monotonic increases in forest loss for each PA since the year 2010.

2.3.2. Change-Point Analyses

We conducted change-point analyses on the tree loss data using package *changepoint*(Killick & Eckley, 2014), to detect PAs that had experienced significant changes in annual proportion of forest loss. Change-point analysis was only carried out for PAs with at least 1% overall loss, and an increasing proportion of annual forest loss (determined by the Mann-Kendall test). In addition to the aforementioned WMAs, Forest Reserves (FRs) were also excluded from these and subsequent analyses as some are used for legal, commercial timber extraction. As a result of this, the pattern of deforestation observed in FRs may be very different from that of other PA types, and not necessarily reflective of long-term habitat loss.

2.3.3. Generalised Additive Model

We built a generalised additive model (GAM) using package *mgcv*(Wood, 2012), to compare the rate of habitat loss across different types of PA and active versus vacant hunting blocks. The GAM included four variables: (1) PA type; (2) hunting status (active hunting block, vacant hunting block, or non-hunting area); (3) travel time to a major city (Malaria Atlas Project(Hay & Snow, 2006)); and (4) annual precipitation (WorldClim Global Climate Data(Fick & Hijmans, 2017)). Travel time and precipitation were included to control for the possibility that areas may be less likely to be converted, regardless of protection, as a result of being further from human settlement or receiving less rainfall.

Travel time and precipitation were smoothed using thin plate regression splines(Wood, 2017), and an extra penalty was added to each smooth term so that it could be penalized to zero, allowing the smoothing parameter estimation to completely remove terms from the model(Marra & Wood, 2011). Smoothing parameters were estimated using restricted maximum likelihood (REML) estimation. Akaike information criterion (AIC) values were used to compare models with and without the parametric variables(Burnham & Anderson, 2002). As the data are proportional, we used a beta regression(Douma & Weedon, 2019). The final model was checked for spatial autocorrelation using the package *ncf*(Bjornstad, 2019) (see Appendix VI).

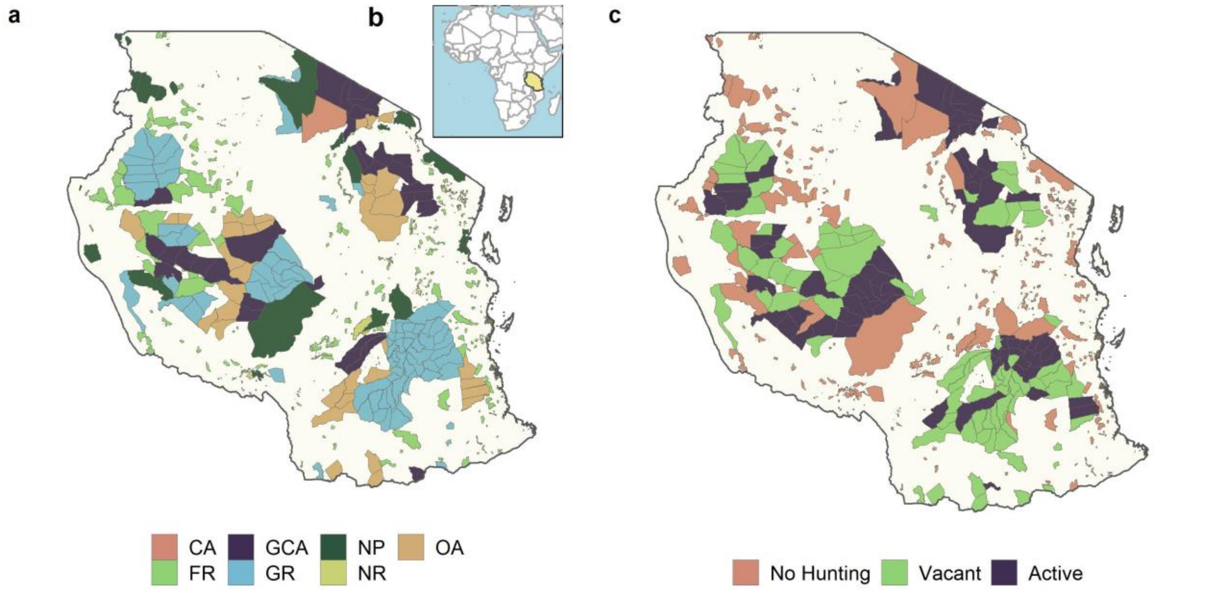

Figure 1: a) Map of protected area (PA) management units in Tanzania, including National Parks and Conservation Areas (NP, CA; primary revenue generating mechanism: non-consumptive use, e.g. photographic tourism), Game Reserves (GR; trophy hunting), Game Controlled Areas, Open Areas and Forest Reserves (GCA, OA, FR; trophy hunting and/or additional limited legal resource extraction, e.g. logging), and National Reserves (NR; limited legal resource extraction). b) The location of Tanzania within Africa. c) Map of hunting status of Tanzanian PA management units, showing those PA units with no hunting, vacant hunting blocks, and active hunting blocks (as of September 2019).

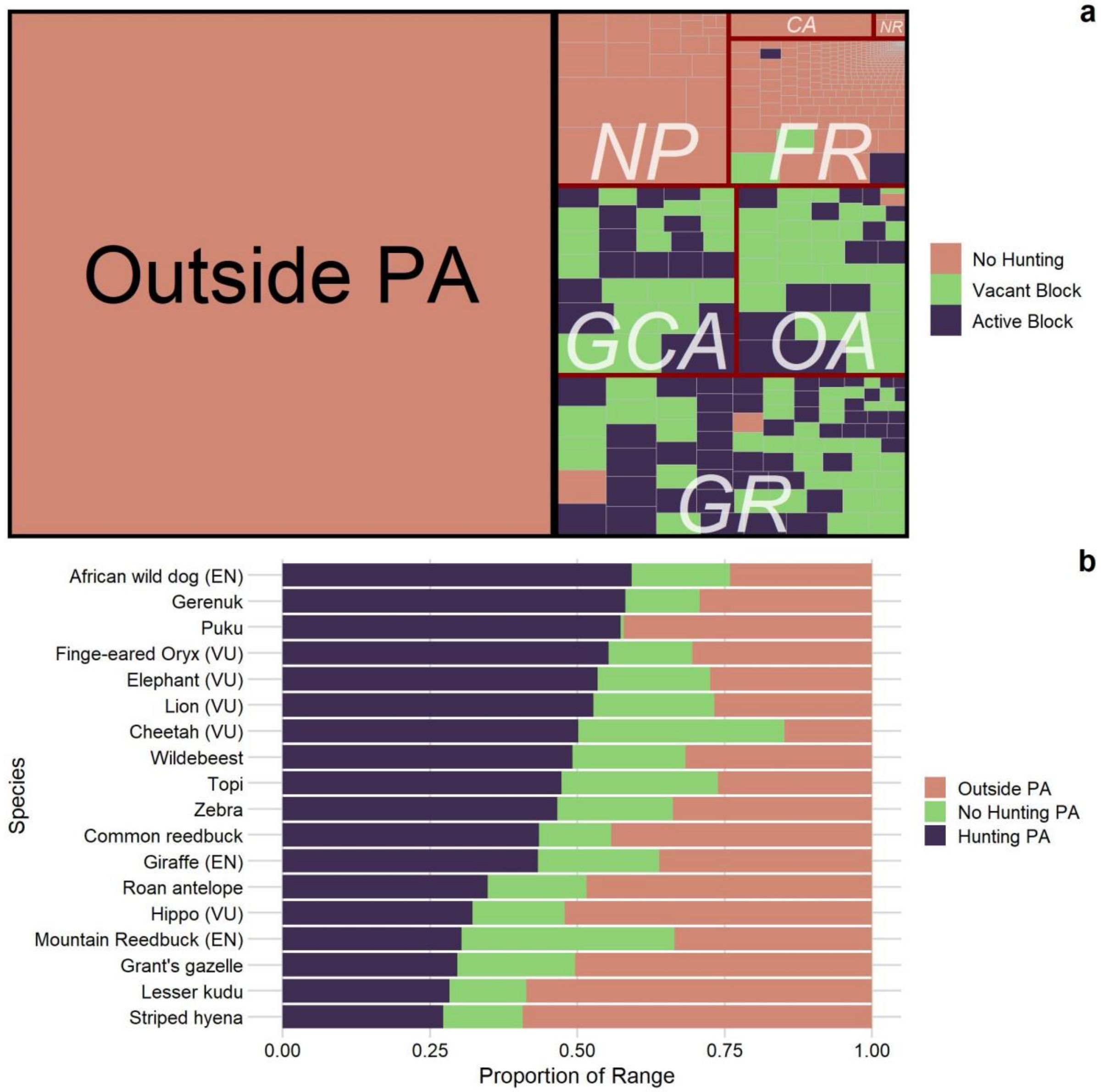

Figure 2: a) Total landmass of Tanzania (km^2), with the size of each rectangle proportional to the area of the Protected Area (PA) management unit. PAs are divided into National Parks (NP), Forest Reserves (FR), Game Controlled Areas (GCA), Open Areas (OA), and Game Reserves (GR). Rectangle colour indicates the presence of trophy hunting and, if present, whether the hunting block was vacant or active in 2018. b) The proportion of Tanzanian range of 18 large mammal species found outside PAs, inside hunting PAs, and inside non-hunting PAs. Species which are listed as vulnerable (VU) or endangered (EN) under the IUCN Red List are labelled.

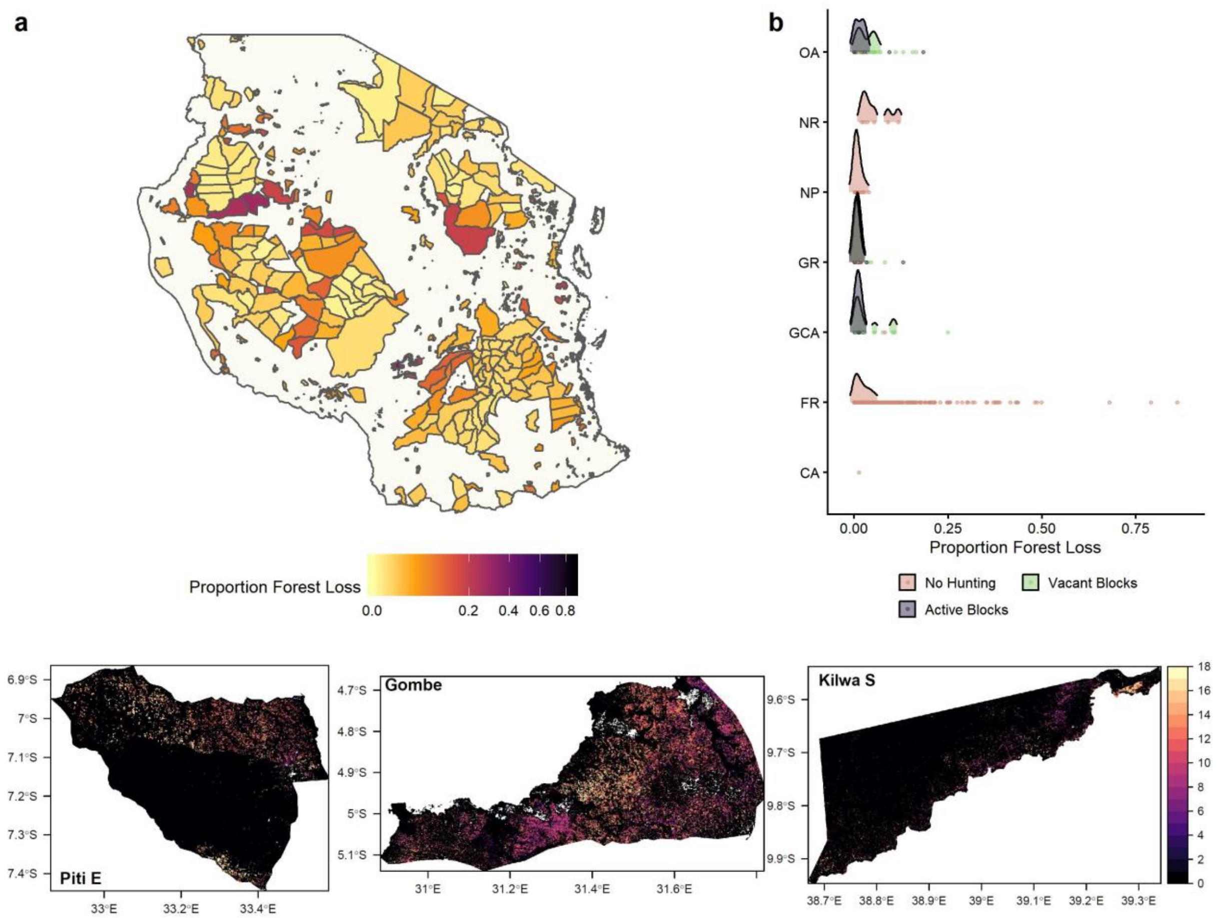

Figure 3: Overall forest loss. a) Map of all Tanzanian PA management units and the total proportion of forest lost between the years 2000-2018. b) Density plot of the total proportion of forest loss for each PA type; results coloured based on whether the PA unit allows hunting, and whether the PA hunting blocks were vacant or active in 2018. NP = National Parks, FR = Forest Reserves, GCA = Game Controlled Areas, OA = Open Areas, GR = Game Reserves, NR = National Reserve, CA = Conservation Area. Bottom: Maps of three hunting PAs in Tanzania which exhibit different patterns of deforestation as described in a hierarchical clustering process (see Appendix IV). The colour scale from 1-18 represents the year (2001- 2018) of deforestation for each 30m resolution pixel. Black pixels have not been deforested and contain at least 10% forest cover, and white pixels represent areas with less than 10% forest cover in the year 2000. Piti East (cluster 3) shows patchy spreading of deforestation (linked to widespread agricultural development) in the north of the PA, with a total loss of 7%. Gombe Open Area (cluster 4) has shown long term losses in forest cover over a much longer period and has 25% total forest lost. Kilwa South (cluster 2) shows patchy and small scale forest loss, totalling 5% forest loss. See Appendix III for breakdowns of the clusters.

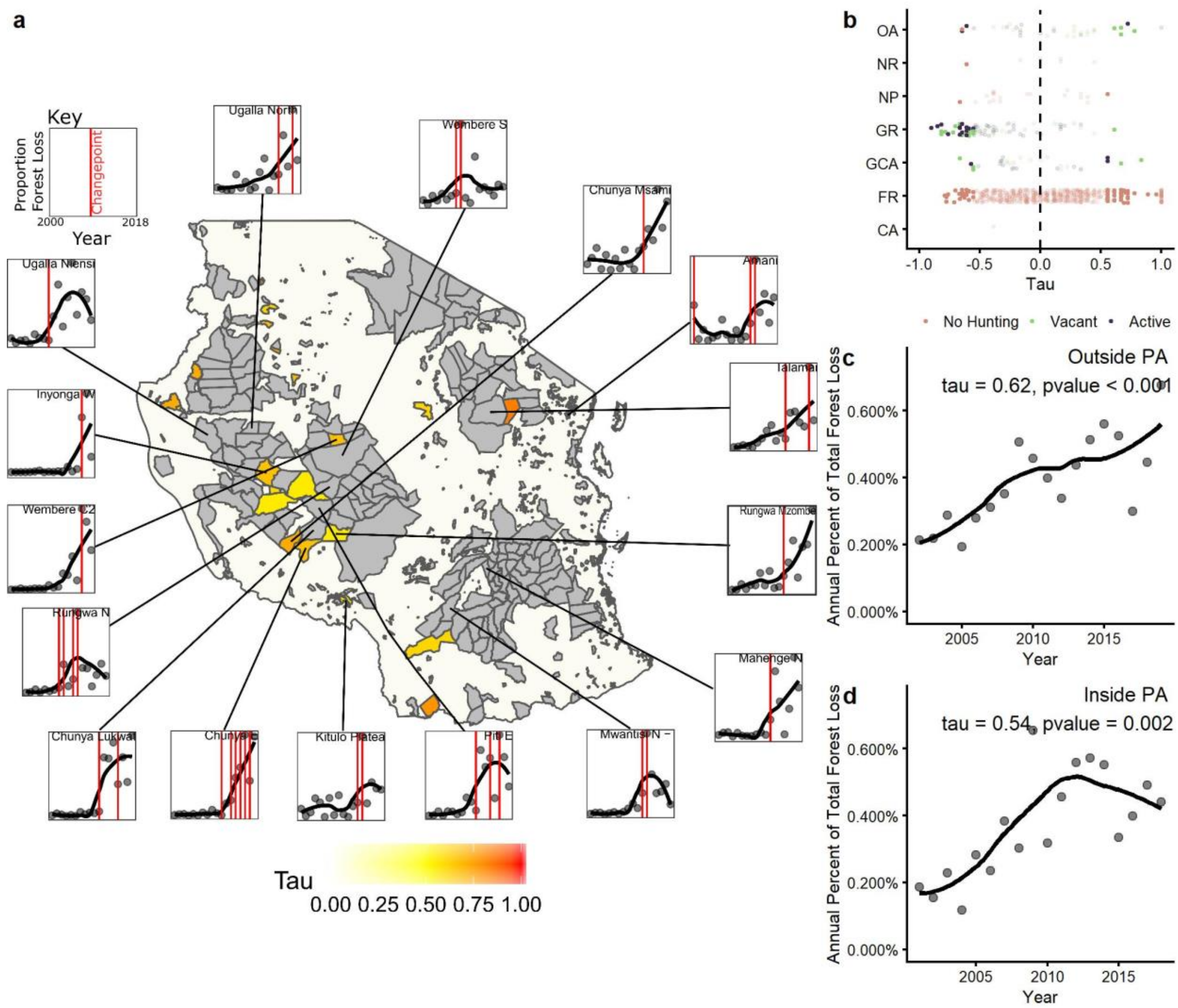

Figure 4. a) A map of Tanzanian PA management units. Each PA unit is coloured by the tau value from a Mann-Kendall test for increases in annual forest loss since the year 2010, only positive and significant tau values at the 95% confidence interval are given. Results from the change-point analysis for each PA unit are displayed around the map. These figures show PA units with at least one change-point detected, and a monotonic increase in deforestation rates since 2010. Each graph demonstrates the proportion of forest loss per PA unit from the year 2001 – 2018, fitted with a Loess regression to visualise the changes. Change-points are displayed with vertical red lines. 16 PA units fit these criteria, with one National Park (Kitulo Plateau), one National Reserve (Amani), 11 Open Areas, and three Game Controlled Areas. Of the 14 PA units that allow hunting (87.5%), 11 are vacant (78.6%). b) The results of the Mann-Kendall test for each PA unit are given, grouped by PA type. The PAs are split into National Parks (NP), Forest Reserves (FR), Game Controlled Areas (GCA), Open Areas (OA), and Game Reserves (GR). The data points for each PA unit are plotted at the value of tau calculated with the Mann-Kendall test, and coloured by the status of hunting within that PA. Those values which are not significant are shaded a lighter colour. c – d) The total annual percent of forest loss each year from 2001-2018 for all of Tanzania outside (c) and inside (d) PAs. A Loess regression is used to visualise the changes in forest loss each year.

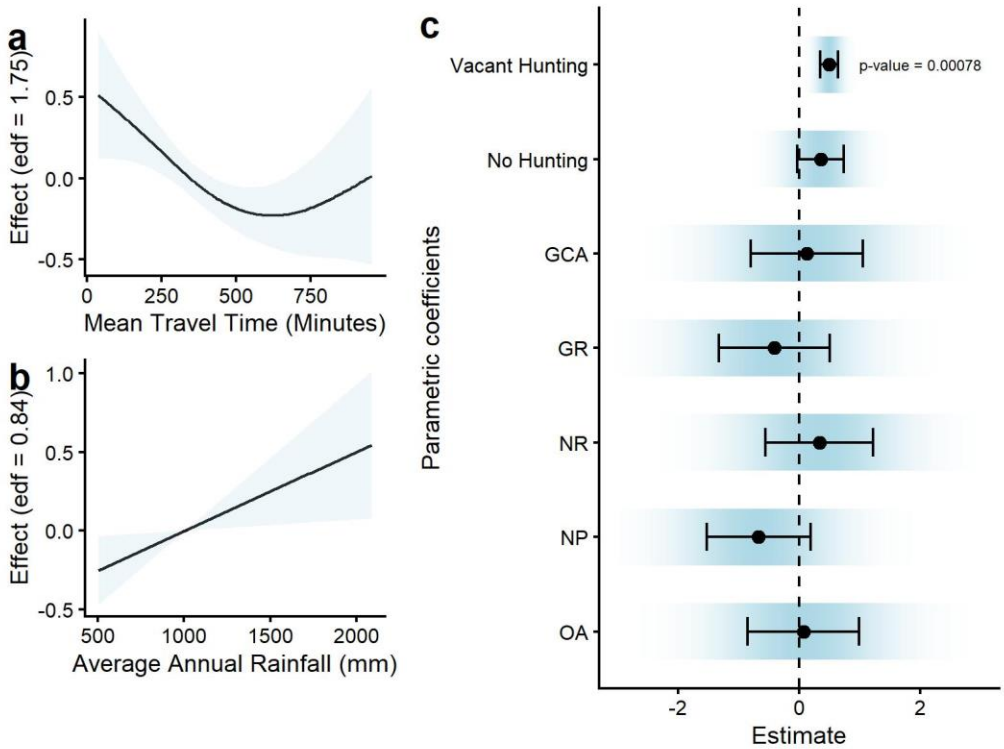

Figure 5: Results of the Generalised Additive Model explaining variation in total forest loss (2000-2018) for Tanzanian PA management units (FRs are excluded from this model). Edf = effective degrees of freedom of each term. a) The effect of mean travel time to the nearest city, showing a significant positive relationship between forest loss and proximity to cities. b) The effect of average annual rainfall (mm) on forest loss, with higher forest loss at higher rainfall. c) The estimated effect size of the different terms in the model. Vacant hunting blocks (regardless of PA type) have a significant positive impact on forest loss from 2000-2018. The width of the error bars gives the standard error of the estimate, with the opacity of the blue background fading to 95% confidence estimates.

3. Results

3.1. Protected area types and hunting status in Tanzania

Our database consisted of a total of 827 individually managed 'units' (denoting separately managed sections within a single PA where relevant, e.g. hunting blocks within a GR), across seven different PA types (Fig. 1; excluding WMAs), covering 370,416 km^2, or 39% of the country (Fig. 2a). As of early 2019, 67.5% of these permitted trophy hunting (249,917 km^2), and 32.5% were reserved for photographic tourism (120,499 km^2; see Table 1). Within hunting areas, 49% were considered to be active hunting blocks, while the remaining 51% were believed to have been vacated by hunting outfitters and not be hunted as of 2018.

3.2. Hunting areas protect considerable large mammal range

For the 18 large mammal species considered, range within non-trophy hunting PAs varied from 0.6% (Puku, *Kobus vardonii*) to 36.1% (Mountain reedbuck, *Redunca fulvorufula*), with a median of 17.9% for all species. Range within trophy hunting PAs varied from 27.2% (Striped hyaena, *Hyaena hyaena*) to 59.2% (African wild dog, *Lycaon pictus*), with a median of 47.0% for all species. Seven species (38.9%) had more than half of their range within hunting areas. Range outside PAs varied from 14.8% (Cheetah, *Acinonyx jubatus*) to 59.3% (Striped hyaena), with a median of 33.6% for all species. All but one (87.5%) of the species classified as vulnerable or endangered had more range in hunting areas than in non-hunting PAs (Fig. 2b; Appendix II).

3.3. Widespread forest loss across Tanzania

Overall, there was 892,374km^2 of forest across Tanzania in the year 2000; 40% in PAs, and 60% in non-PAs. The 827 PA management units considered in this study lost 11,598km^2 of forest cover since 2000 (3.23%); non-PA land lost 36,549km^2 of forest cover (6.85%) over the same period (Fig. 3). Within PAs, forest loss was generally highest in FRs (8.1% of total), GCAs (3.52%), OAs (6.44%), and NRs (3.45%), with lower losses in more strictly-protected photographic (NPs, 0.61%; NCA, 1.3 %), and trophy hunting (GRs, 0.79%) areas (Fig. 3 & Table 1).

3.4. Rapid forest loss in semi-protected PAs

We found a significant positive monotonic trend in the rate of forest loss both outside (tau = 0.621, p<0.005) and inside PAs (tau = 0.542, p<0.005), with annual forest loss increasing in both cases from

~0.2% in 2001 to ~0.6% in 2018 (Fig. 4c-d). Annual proportions of forest loss did not differ inside PAs versus outside PAs (V = 99, p=0.2899); however, rates of forest loss within PAs seem to have plateaued and decreased since 2012 (Fig. 4d). Several PAs were identified as having undergone a significant increase in the rate of forest loss during the study period, including 36 FRs, two vacant GCAs, two active GCAs, one vacant GR, one NP, one active OA, and four vacant OAs (Fig. 4B; Appendix III). Sixteen PAs fit our change-point analysis criteria; one NP (Kitulo Plateau), one NR (Amani), 11 OAs, and three GCAs. Of the 14 PAs among these that allow hunting (87.5%), 11 are vacant (78.6%).

3.5. Vacant hunting blocks have lost the most forest cover

A Generalised Additive Model (GAM) best explained forest loss in Tanzanian PAs with both PA type (i.e. NP, GR, etc.) and hunting status (hunted-active, hunted-vacant, or non-hunted), and included both travel time to a major city and annual precipitation (Appendix VI). Specifically, forest loss between the years 2000-2018 was associated with areas closer to major cities (Fig. 5a, $p<0.005$), in areas with higher rainfall (Fig. 5b, $p=0.0123$) and in hunting PAs which were vacant (Fig. 5c, $p<0.005$). The effect size of vacant blocks (0.495) is similar to that of PAs that are directly adjacent to cities, or which have greater than 1500mm of rainfall. The effect of vacant hunting blocks was the only effect amongst PA type which was significant (Fig. 5c).

Table 1: Description of the different PA types in Tanzania, with overall forest cover (at the 10% forest threshold), overall forest loss from 2000-2018, and changes to the rates of forest loss.

Type	Strict Protection?	Primary revenue-generation mechanism	Number of management units[1]	Area (km^2)	Percentage of country (%)	Initial area with 10% forest cover (km^2)	Forest loss (km^2)	% loss	Trophy hunting status	Number with increasing forest loss since 2010
National Park (NP)	Yes	Non-consumptive (e.g. photographic) tourism	20	60,617	6.44	60,247.54	369.63	0.61	Non-hunting	1
Conservation Area (CA)	Yes	Non-consumptive (e.g. photographic) tourism	1	8,250	0.88	8,144.35	105.58	1.30	Non-hunting	0
Game Reserve (GR)	Yes	Trophy hunting	85	114,108	12.1	113,212.63	894.99	0.79	Non-hunting	0
									Hunting – active	0
									Hunting – vacant	1
Forest Reserve (FR)	No	Trophy hunting and/or limited legal resource extraction (e.g. logging)	644	52,305	5.56	48,388.08	3,916.72	8.09	Non-hunting	35
									Hunting – active	0
									Hunting – vacant	1
National Reserve (NR)	No	Limited legal resource extraction (e.g. logging)	6	1,996	0.21	1,929.54	66.49	3.45	Non-hunting	0
Game Controlled Area (GCA)	No	Trophy hunting and/or limited legal resource extraction (e.g. logging)	33	68,360	7.26	66,033.71	2,326.62	3.52	Hunting – active	2
									Hunting – vacant	2
Open Area (OA)	No	Trophy hunting and/or limited legal resource extraction (e.g. logging)	37	64,780	6.88	60,862.42	3,918.01	6.44	Non-hunting	0
									Hunting – active	1
									Hunting – vacant	4
PA Management Units (excluding WMAs)			**827**	**370,416**	**39.3**	**358,818.26**	**11,598.04**	**3.23**		**47**
Non-PA				**571,089**	**60.7**	**533,555.47**	**36,548.70**	**6.85**		
Total				**941,505**	**100.00**	**892,373.73**	**48,146.74**	**5.40**		

[1] “Management units” denotes separately managed sections within a single PA, e.g. individual hunting blocks within a GR, as shown in Fig. 1

4. Discussion

4.1. Forest loss has been considerable in Tanzania

Our findings reveal substantial losses of habitat both outside and inside Tanzania's PAs, with 5.4% (48,150 km^2) of the country's forest cover lost from 2000 to 2018. This wide-scale loss of forest cover is particularly concerning given the importance of forests for the provision of essential ecosystem services, such as carbon sequestration(Maxwell et al., 2019). Much of this loss is likely to be a result of agricultural expansion(Masanja, 2014; Shackelford et al., 2015). Our findings further support this, with forest loss was greater in PA management units with higher rainfall and closer to major settlements, where agricultural production is the most profitable (Fig. 4).

4.2. Strictly protected areas experience less degradation

Within PAs, forest loss was lowest within strictly-protected PA management units (Table 1), whether allocated for photographic tourism (NPs) or trophy hunting (GRs), although neither of these was significant in the GAM. Of the PA management units which have seen continual increases in forest loss (Fig. 3), the majority (96%, n = 43) of these were semi-protected areas, and only two of the 16 PA management units which have seen recent large spikes in forest loss detected by our change-point analysis (Fig.4a) were strictly-protected PAs (one of these, Kitulo Plateau NP, was only established in 2005). This reflects previous findings highlighting the effectiveness of strict protection for avoiding habitat loss in East Africa(Riggio et al., 2019). Given the vast amount of land that these strictly-protected PAs cover (19.4% of Tanzania; ~183,000 km^2), and the relatively high revenue they generate through photographic tourism and/or trophy hunting, it is positive that they appear relatively effective at curtailing habitat loss. On the other hand, however, the rates of loss observed in semi-protected areas should be of concern, given the high proportion of the country currently under this management structure (18.6%; 175,843 km^2).

4.3. The tenure of hunting blocks is a critical determinant of forest loss

Hunting block tenure (i.e. whether the block was actively hunted or remained vacant) was an important predictor of forest loss, with significantly higher rates of loss within vacant hunting areas. Additionally, 7 of the 10 hunting areas that showed significant continuous increases in the rate of forest loss, and 11 of the 14 which experienced rapid increases in the rate of loss, were vacant.

Overall, these patterns of forest loss are concerning considering that the majority of protected land in Tanzania consists of either semi-protected hunting areas (12.1%) or strictly-protected hunting areas (19.7%; note that this proportion has changed since September 2019 as a result of changes in the status of a number of PAs, such as the gazetting of 30,000km^2 of Selous GR as Nyerere NP in November 2019(Kimboy, 2019)). This is highlighted by our analysis of large mammal distribution: for all of the 18 large mammal species we assessed, an important proportion of their range was found within hunting PAs (Fig. 2a). Our results thus reveal that land within areas currently allocated for trophy hunting is of critical importance to the conservation of large mammals in Tanzania, highlighting the seriousness of the observed patterns of loss. Furthermore, many of the areas experiencing the highest loss coincide with wildlife and migratory corridors(Riggio & Caro, 2017). For example, some of the highest and most rapidly increasing rates of loss occurred in the semi-protected vacant hunting PAs which form corridors between the strictly-protected Ruaha-Rungwa and Katavi-Rukwa conservation complexes (Fig. 3). Habitat loss within these PAs will therefore not only impact resident wildlife but also jeopardises remaining connectivity for large mammal populations within strictly-protected PAs across the country.

4.3.1. Drivers of forest loss in vacant blocks

The higher observed rates of forest loss in vacant hunting blocks are likely due to two economic factors: management costs and opportunity costs(Michael Norton-Griffiths & Said, 2009). First, in these areas, there is likely a lack of sufficient financial support for PA management to prevent encroachment within PA boundaries. In hunting areas, operators must contribute towards PA management through anti-poaching and other protection activities(Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2016), and there is evidence that law enforcement activities are lower in those hunting areas that have been vacated(Ruaha Carnivore Project, 2019). Additionally, trophy hunting is the primary source of income for the Tanzania Wildlife Management Authority (TAWA), which is responsible for the management of all of Tanzania's PAs which are not NPs, FRs, or the NCA, with 80% of TAWA's anti-poaching budget reported to come directly from hunting revenues(Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2016). Thus, hunting area vacancy not only means that hunting operators are not helping to enforce PA rules, but also reduces funds available to the national government authority responsible for the areas' protection in their absence. Second, without significant revenue generation, these PAs are unlikely to be overcoming their growing opportunity costs at both the national and local level. At the national level, there is likely to be considerably less political will to maintain these loss-making PAs in the face of alternative land use options. This is particularly the case in countries with rapidly expanding economies, like Tanzania, where national sustainable development priorities, agricultural expansion and large infrastructural projects to meet the demands of a growing population, also require land(Riggio et al., 2019; United Nations, 2019). Moreover, if local communities in and around PAs derive little benefit from PAs, there is often little rationale to not exploit natural resources and convert these PAs to alternative land uses, which potentially deliver more immediate and visible benefits to rural people(Di Minin et al., 2016; Fisher et al., 2011; Green et al., 2018; Peter Andrew Lindsey et al., 2012; Mascia et al., 2014; Michael Norton-Griffiths & Said, 2009). In this context, the recent changes in hunting block tenure in Tanzania are particularly concerning. Without hunting, incentives to conserve the large tracts of habitat within hunting blocks are being removed.

The underlying drivers of the observed rise in hunting block abandonment is a source of debate. Many stakeholders have cited the impact of US and European trophy import bans and restrictions as a critical factor in decreasing demand, due to anti-hunting campaigns and shifting ethical norms in Western society, while economic recessions have also been argued to have an effect(Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2016),(Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2018). They argue that the reduced demand for hunting resulted in them having to leave their blocks vacant, and this, in turn, resulted in less on-the-ground protection.

However, there is also evidence that some vacated hunting areas became no longer economically viable while being actively hunted due to depletion of wildlife – attributed to unscrupulous hunting practices, poor management, or excessive human pressure – and other barriers to financial viability, such as unfavourable tenure policies(Booth, 2017; Brink et al., 2016). Furthermore, observed patterns of loss in some areas that continue to be actively hunted suggest that the current framework may not allow for sufficient revenue generation to fully fund management of these PAs, even without added pressures(Peter A. Lindsey et al., 2016). This is perhaps not surprising: very few PAs are able to generate enough funding from any form of tourism to cover management costs at the site level. Trophy hunting generates important income for PAs, and for some hunting companies, but increasingly, the revenue generated is insufficient to allow for a sufficiently high standard of management and to cover the associated government fees, without philanthropic subsidies(Peter A. Lindsey et al., 2016). The same is likely true for photographic tourism in most PAs, except for the most visited parks[21]. A limitation of our study is that we are unable to distinguish whether habitat loss began after hunting blocks were abandoned, or if hunting blocks were abandoned as a consequence of pre-existing habitat loss, wildlife depletion, or poor management. We, therefore, urge future research to consider information on other forms of anthropogenic impacts which could be contributing to habitat loss and decreases in wildlife, including all forms of unsustainable killing of wildlife, and land uses which degrade habitat, and result in wildlife declines even within PAs(Craigie et al., 2010b; Ogutu et al., 2016). Nevertheless, the recent (since 2014) spikes in forest loss in many vacant or poorly protected blocks (Fig. 4A) indicate that habitat loss increased sharply at the time of widespread block abandonment, supporting the hypothesis that abandonment was a key driver of habitat loss.

It is also worth noting that our analysis assessed mammal distribution based on range maps; however, there is evidence that species generally exist at higher densities in strict PAs than semi-protected PAs in Tanzania(Stoner et al., 2007). This is of particular relevance to hunting PAs, where species often exist at lower densities than in areas reserved for photographic tourism(Balme et al., 2010; Loveridge et al., 2016). As such, the relative ability of different PA types to safeguard wildlife populations needs further investigation, ideally through studies into differences in finer-scale metrics of status (such as population densities or occupancies) between PA types.

4.4. Large scale and novel funding mechanisms are needed to safeguard biodiversity

Tanzania has committed almost half of its land area to conservation (Fig. 1), but must also commit resources to its sustainable development priorities as its economy and population continue to grow, which will also cause the opportunity costs of conservation to increase(Fisher et al., 2011; Green et al., 2018). Considering the size and extent of PAs, their already inadequate budgets, and the large costs associated with their preservation, we warn against shifting away from potential sources of revenue for conservation-oriented land management, such as trophy hunting, without ensuring appropriate alternative revenue-generating mechanisms have first been identified and put in place(Di Minin et al., 2016; A. Dickman et al., 2019). At the same time, the international community benefits greatly from the preservation of biodiversity and ecosystem services, especially the sequestration of carbon from intact habitat(Fisher et al., 2011). The international community should be encouraged to collaborate with Tanzania's wildlife management and conservation authorities to explore novel conservation-oriented revenue-generating solutions for PAs, and contribute towards the vast costs of conservation, shouldered predominantly by poor, local communities, and the national government(Green et al., 2018; Peter A. Lindsey et al., 2018, 2014; Waldron et al., 2017). Some hunting areas may be able to benefit from increased international photographic tourism, but alternative revenue-generating mechanisms must be sought for the hundreds of thousands of square kilometres of habitat which remain within hunting blocks not suitable for photographic tourism (for a range of reasons(P. A. Lindsey et al., 2007; P.A. Lindsey et al., 2006; Ministry of Natural Resources and Tourism (MNRT) of the United Republic of Tanzania, 2012, 2016)). Opportunities may include debt for nature swaps, Payment for Ecosystem Services (of particular interest are carbon payments), a Conservation Basic Income, private philanthropy, or sustainable livestock-wildlife systems(Buscher & Fletcher, 2020; Crossman et al., 2011; Keesing et al., 2018; Pringle, 2017; Venter et al., 2009; Western et al., 2020). In this context, legislative changes encouraging public-private partnerships for management of vacant hunting blocks may represent a particularly important and promising tool for promoting externally-funded conservation-friendly land use strategies while providing tangible economic value(Baghai et al., 2018; Peter A. Lindsey et al., 2018). While the immediate loss of trophy hunting revenue is a pressing concern, most PAs, including those generating revenue from photographic tourism, already need further investment and subsidies to meet their management and opportunity costs(Green et al., 2018; M. Norton-Griffiths et al., 2009). The fragility of the existing system, and its reliance upon foreign tourism, has been brought into sharp relief by the COVID-19 pandemic, reinforcing the need for additional and more resilient conservation funding mechanisms.

To achieve this, broader cross-sectoral planning is needed within a landscape theory framework(Arts et al., 2017) to promote the prioritisation of conservation and development interventions, with PA investments prioritised based on a range of factors – including wildlife, carbon, water, and people – to secure areas whose continued protection is essential to attain the nation’s biodiversity targets while achieving its development goals. Efforts should also be made to encourage a spectrum of other effective area-based conservation measures (OECMs(Dudley et al., 2018)) which devolve management and benefits to local communities, ensuring that there still exists a space for biodiversity and wildlife within these working landscapes without compromising Tanzania’s continued sustainable development priorities(Kremen & Merenlender, 2018; Tilman et al., 2017; Western et al., 2020).

4.5. Conclusions

We show that even in Tanzania – which has the largest proportion of land under some form of protection of any African country, considerably exceeding the threshold of protection set out in Aichi Target 11(CBD, 2010) – continued protection of the country's ecosystems and biodiversity remains precarious. Even within a country so strongly committed to conservation, the weight of ongoing demographic and economic changes are such that under-resourced PAs will almost certainly be overcome by human pressures as demand for land continues to grow. This scenario, coupled with the lack of funding for PAs, puts the future of PAs, biodiversity and ecosystem function at risk, not just in Tanzania, but also in the numerous countries which face similar challenges. Continued under-resourcing will greatly limit the ability of many nations, especially in SSA, to meet the post-2020 biodiversity targets and Sustainable Development Goals. To reach the protected area requirements of the post-2020 targets, which could amount to as much as 44% of the Earth's terrestrial surface(Allan et al., 2019), considerable investment will be needed to ensure the economic viability of PAs and OECMs within SSA. At a time of increasing pressure on some revenue-generating activities such as trophy hunting, it is both imperative and urgent that any decrease in those activities and the revenue they generate should be matched with commitments to replace and increase the funding of PAs, to avoid further declines in SSA invaluable PAs and the biodiversity and livelihoods they support.

Conflict of Interest

AD is the Director of the Ruaha Carnivore Project in Tanzania, which has received minor past funding from hunting and non-hunting tourism companies, amongst many other donors. All other authors declare no conflict of interest.

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Appendix I

Tanzanian Protected Area Types

Tanzania has the largest proportion of land protected of any African country[1], with PAs covering approximately 48.2% of its terrestrial area[2]. This is nearly three times the Convention of Biodiversity Aichi Target 11 of 17% protection of terrestrial areas[3]. Tanzania's commitment to conservation means it is still one of the world's most biodiverse countries, particularly for large mammals, supporting two of the world's 35 globally recognised biodiversity and endemism hotspots[4], 18 different ecoregions[5], a third of Africa's total plant species[6], and the twelfth highest number of bird species by country[7]. Tanzania is home to at least 340 mammal species, including significant populations of threatened and charismatic large mammals[8]. These include all large carnivore species found in Eastern and Central Africa – including Africa's largest remaining number of wild lions[9] – and some of Africa's most important remaining elephant populations[10]. However, under scenarios of economic development and demographic change, much of Tanzania is at risk of land use change to meet growing economic demands[11].

- **National Park (NPs),** reserved for non-consumptive utilisation (e.g. photographic tourist safaris), with no settlement or resource utilisation of any type permitted within their boundaries. NPs are generally the best protected of Tanzania's PAs.
- **Ngorongoro Conservation Area (NCA)**, also reserved for non-consumptive utilisation, but with the exception of Maasai pastoralists, who are permitted to reside within its boundaries. Much like in the case of NPs, protection levels are relatively high.
- **Game Reserves (GRs),** managed for trophy hunting, with a few exceptions. Much like NPs, GRs prohibit any permanent human settlements, grazing of livestock, or extraction of natural resources. Effective protection levels experienced in GRs vary greatly across the country, but GRs generally receive the most conservation attention after NPs, NRs and the NCA.
- **Game Controlled Areas (GCAs)** & **Open Areas (OAs),** where human settlement and grazing of livestock are unrestricted, and both trophy hunting and limited extraction of natural resources by local communities (e.g. logging) are permitted under licence (as in completely non-protected areas). Encroachment and land conversion to agriculture are increasingly common in some areas.
- **Wildlife Management Areas (WMAs),** consisting of areas on village land set aside for wildlife conservation, where communities decide how the land should be managed and revenue accrued (e.g. photographic tourism, trophy hunting, limited resource extraction, etc.).

- **Forest Reserves (FRs),** where limited resource extraction, mostly in the form of logging, be permitted. As in the case of GCAs and OAs, protection in FRs is generally very low, and regulations regarding resource extraction between areas vary greatly.

- **Nature Reserves (NRs),** consisting of areas strictly set aside to protect biodiversity and possibly geological/geomorphological features, where human visitation, use and impacts are strictly controlled and limited to ensure the protection of conservation values. Such protected areas serve as indispensable reference areas for scientific research and monitoring.

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Appendix II

Large Mammal Species

Table II.1: The 18 large mammal species considered in this study, showing IUCN status & population trend and the proportion of Tanzanian range in non-hunting PA, hunting PA, and non-PA.

Common name	Latin name	IUCN status	Population trend	Total TZ range (km^2)	Range in non-hunting PA (km^2)	Range in non-hunting PA (%)	Range in hunting PA (km^2)	Range in hunting PA (%)	Range in non-PA (km^2)	Range in non-PA (%)
African wild dog	*Lycaon pictus*	EN	Decreasing	255,450.30	42,779.96	16.75	151,233.94	59.20	61,436.39	24.05
Maasai giraffe	*Giraffa camelopardalis (tippelskirchi)*	EN	Decreasing	322,305.52	66,270.09	20.56	139,728.60	43.35	116,306.83	36.09
Mountain reedbuck	*Redunca fulvorufula*	EN	Decreasing	62,300.35	22,516.53	36.14	18,922.57	30.37	20,861.25	33.48
African elephant	*Loxodonta africana*	VU	Increasing	317,517.72	60,654.73	19.10	169,695.75	53.44	87,167.24	27.45
Cheetah	*Acinonyx jubatus*	VU	Decreasing	118,580.87	41,539.41	35.03	59,481.14	50.16	17,560.32	14.81
Fringe-eared oryx	*Oryx beisa (callotis)*	VU	Decreasing	73,652.42	10,415.55	14.14	40,764.93	55.35	22,471.94	30.51
Hippopotamus	*Hippopotamus amphibius*	VU	Stable	145,860.22	22,796.95	15.63	46,989.73	32.22	76,073.54	52.16
Lion	*Panthera leo*	VU	Decreasing	382,757.22	78,449.19	20.50	201,813.83	52.73	102,494.20	26.78
Gerenuk	*Litocranius walleri*	NT	Decreasing	66,552.94	8,417.69	12.65	38,682.44	58.12	19,452.82	29.23
Lesser kudu	*Tragelaphus imberbis*	NT	Decreasing	182,424.72	23,875.54	13.09	51,602.92	28.29	106,946.25	58.62
Plains zebra	*Equus quagga*	NT	Decreasing	402,672.57	79,249.57	19.68	187,526.91	46.57	135,896.10	33.75
Puku	*Kobus vardonii*	NT	Decreasing	23,214.38	134.94	0.58	13,310.77	57.34	9,768.67	42.08
Striped hyaena	*Hyaena hyaena*	NT	Decreasing	541,550.14	72,979.12	13.48	147,493.88	27.24	321,077.13	59.29
Common wildebeest	*Connochaetes taurinus*	LC	Stable	194,518.63	37,328.30	19.19	95,651.04	49.17	61,539.29	31.64
Grant's gazelle	*Nanger granti*	LC	Decreasing	200,229.31	40,034.88	19.99	59,341.09	29.64	100,853.34	50.37
Roan antelope	*Hippotragus equinus*	LC	Decreasing	347,018.48	58,273.99	16.79	120,833.74	34.82	167,910.75	48.39
Southern reedbuck	*Redunca arundinum*	LC	Stable	303,055.63	37,133.27	12.25	131,743.50	43.47	134,178.86	44.28
Topi	*Damaliscus lunatus*	LC	Decreasing	111,982.33	29,684.15	26.51	53,021.42	47.35	29,276.77	26.14

Appendix III

Individual Protected Area Details

This file gives the details of PA’s used in the analysis, including:

- PA Name
- Type of PA
- PA hunting status
- Vacancy of hunting blocks
- Area of PA
- Orginal percentage of forest cover (2000)
- Percentage of forest cover lost (2001-2018)
- Results of the Mann-Kendall trend test with the value Tau, and p-value reported

Forest_Loss_TZ_perPA.csv

Appendix IV

Patterns of Loss – Landscape Metrics & Principal Component Analysis (PCA)

Methodology

To extract indicators of landscape structure with information theory metrics, and to explore patterns of deforestation across PA types we used package *landscapemetrics* (Hesselbarth et al., 2019). Four metrics were considered:

- **Marginal entropy** [H(x)], which represents a diversity (thematic complexity, composition) of spatial categories. It is calculated as the entropy of the marginal distribution.
- **Conditional entropy** [H(y|x)], which represents a configurational complexity (geometric intricacy) of a spatial pattern. If the value of conditional entropy is small, cells of one category are predominantly adjacent to only one category of cells. On the other hand, a high conditional entropy value shows that cells of one category are adjacent to cells of many different categories.
- **Joint entropy** [H(x, y)], an overall spatio-thematic complexity metric. This metric represents the uncertainty in determining a category of the focus cell and the category of the adjacent cell. In other words, it measures diversity of values in a co-occurrence matrix – the smaller the diversity, the larger the value of joint entropy.
- **Mutual information** [I(y,x)], which quantifies the information that one random variable (x) provides about another random variable (y). This metric tells us how much easier is to predict a category of an adjacent cell if the category of the focus cell is known, and disambiguates landscape pattern types characterised by the same value of overall complexity.

We applied a hierarchical clustering algorithm on these metrics and the total proportion of forest loss, and generated diagnostic plots using packages *FactoMineR* (Lê et al., 2008) and *factoextra* (Kassambara and Mundt, 2019) to specify the optimal cluster numbers.

Results

Based on the patterns of forest loss between 2001 and 2018, six main PA groups were identified, as well as two individual PAs with distinct patterns (Fig. 9)

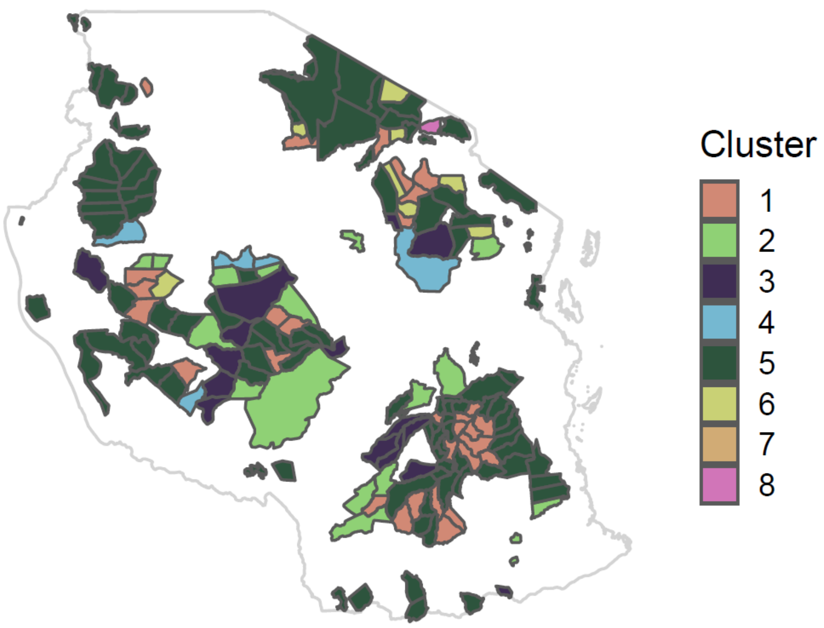

Fig. III.1: PCA cluster groups based on patterns of deforestation between 2000 and 2018. 1 = Areas with low forest loss (including those with lower initial forest cover); 2 = Areas with slightly higher but patchy forest loss; 3 = Areas with higher forest loss, experiencing clustered patches of loss (possibly indicative of habitat conversion to agriculture); 4 = Areas with the highest rate of forest loss, also experiencing clustered patches of loss (possibly indicative of habitat conversion to agriculture); 5 = Areas with low distributed forest loss; 6 = Areas with low forest loss (including those with lower initial forest cover); 7 and 8 = Individual PAs Msima GCA and Ngaserai OA with very low initial forest cover.

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Appendix V

Change-Point Analysis

Table V.1: The 16 PAs that fit our change-point analysis criteria (PAs, excluding FRs and WMAs, with at least 1% overall loss, and an increasing proportion of annual forest loss as determined by the Mann-Kendall test). NP = National Park, GCA = Game Controlled Area, OA = Open Area, NR = National Reserve.

	Name	Vacant	HuntArea	Status
1	Chunya Msami	No	Yes	OA
2	Inyonga W	Yes	Yes	GCA
3	Ugalla Niensi	Yes	Yes	OA
4	Ugalla North W	Yes	Yes	OA
5	Rungwa N	Yes	Yes	OA
6	Rungwa Mzombe	No	Yes	GCA
7	Talamai	Yes	Yes	OA
8	Mwantisi N - Furua	Yes	Yes	OA
9	Wembere S	Yes	Yes	GCA
10	Wembere C2	Yes	Yes	OA
11	Chunya E	Yes	Yes	OA
12	Chunya Lukwati	No	Yes	OA
13	Piti E	Yes	Yes	OA
14	Mahenge N	Yes	Yes	OA
15	Kitulo Plateau	NA	No	NP
16	Amani	NA	No	NR

Appendix VI

Explaining Loss – Generalised Additive Model (GAM)

Table VI.1: GAM model rankings, where Type refers to the PA type and Hunt Status refers to either: no hunting, vacant block, or active block. AIC is Akaike information criterion, and df represents the models degrees of freedom.

Model		**df**	**AIC**	
Type + HuntStatus + Precipitation + Time		12.26944	-1097.47	
Type + Precipitation + Time		8.142641	-1089.3	
HuntStatus + Precipitation + Time		10.09121	-1090.96	
Precipitation + Time		5.403344	-1082.72	

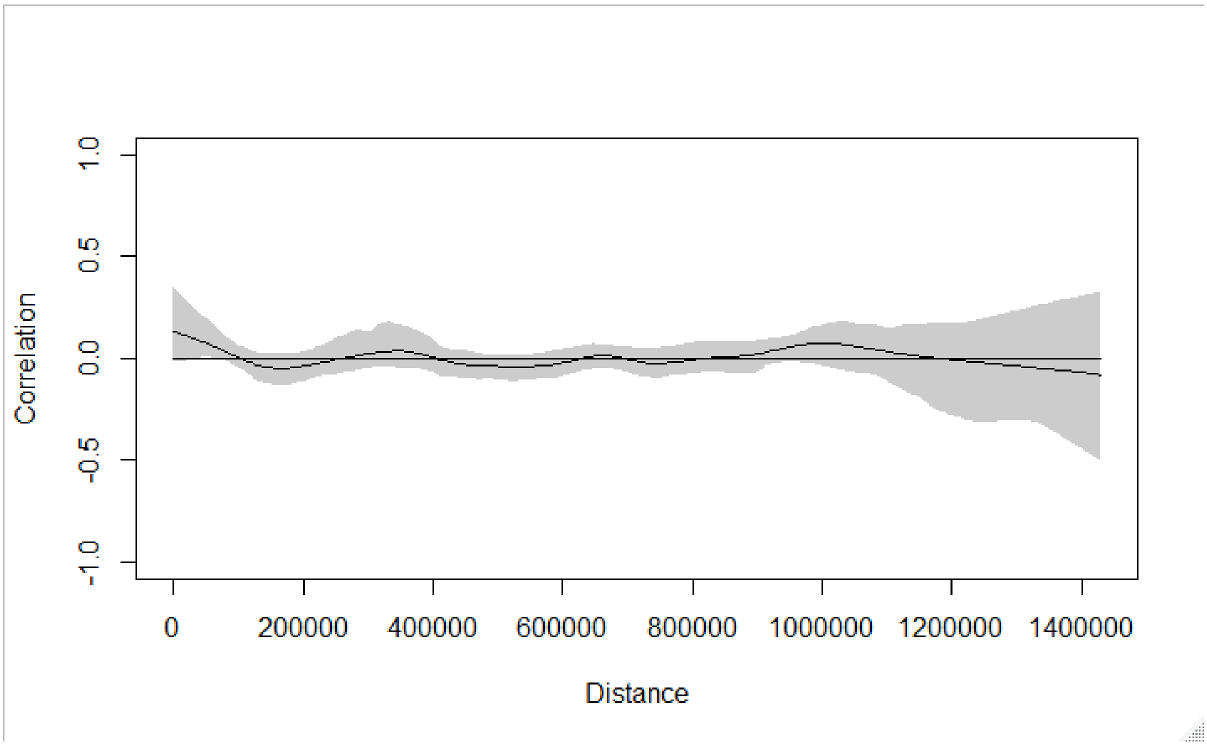
Table VI.2: The non-parametric smooth terms from the final generalized additive model explaining forest loss. edf is the estimated degrees of freedom for each term.

Term	**edf**			**p.value**
s(mean_travel_time)	1.75			0.00483
s(mean_precipitation)	0.842			0.0123

Table VI.3: Parametric terms, the parameter estimates, their standard errors, and the p-value from the final generalized additive model.

Term	**Estimate**	**std.error**	**statistic**	**p.value**
(Intercept)	-3.92	0.92	-4.27	1.97E-05
Non-trophy Hunting	0.354	0.386	0.917	0.359
Vacant Block	0.495	0.147	3.36	0.000776
GCA	0.127	0.923	0.137	0.891
GR	-0.413	0.914	-0.452	0.651
NP	-0.668	0.86	-0.777	0.437
NR	0.335	0.889	0.377	0.706
OA	0.0692	0.919	0.0753	0.94

Figure V1.1: Cross-correlogram from the final fitted GAM model, indicating little spatial autocorrelation exists in the residuals.



Appendix VII

Forest Loss Data Maps for Tanzanian PAs

Forest loss maps (2000-2018) for all PAs in Tanzanian included in the study can be accessed at:

(ORA link)