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Deforestation and Connectivity among Protected Areas of Tanzania

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Abstract: Protected Areas (PAs) in Tanzania had been established originally for the goal of habitat, landscape and biodiversity conservation. However, human activities such as agricultural expansion and wood harvesting pose challenges to the conservation objectives. We monitored a decade of deforestation within 708 PAs and their unprotected buffer areas, analyzed deforestation by PA management regimes, and assessed connectivity among PAs. Data came from a Landsat based wall-to-wall forest to non-forest change map for the period 2002–2013, developed for the definition of Tanzania's National Forest Reference Emissions Level (FREL). Deforestation data were extracted in a series of concentric bands that allow pairwise comparison and correlation analysis between the inside of PAs and the external buffer areas. Half of the PAs exhibit either no deforestation or significantly less deforestation than the unprotected buffer areas. A small proportion (10%; *n* = 71) are responsible for more than 90% of the total deforestation; but these few PAs represent more than 75% of the total area under protection. While about half of the PAs are connected to one or more other PAs, the remaining half, most of which are Forest Reserves, are isolated. Furthermore, deforestation inside isolated PAs is significantly correlated with deforestation in the unprotected buffer areas, suggesting pressure from land use outside PAs. Management regimes varied in reducing deforestation inside PA territories, but differences in protection status within a management regime are also large. Deforestation as percentages of land area and forested areas of PAs was largest for Forest Reserves and Game Controlled areas, while most National Parks, Nature Reserves and Forest Plantations generally retained large proportions of their forest cover. Areas of immediate management concern include the few PAs with a disproportionately large contribution to the total deforestation, and the sizeable number of PAs being isolated. Future protection should account for landscapes outside protected areas, engage local communities and establish new PAs or corridors such as village-managed forest areas.

Keywords: deforestation; isolation; protected areas; buffer areas; Tanzania

1. Introduction

Overwhelming evidence shows that Protected Areas (PAs) in the form of either National Parks, Forest Reserves or other forms of protection have lower deforestation rates than unprotected landscapes [1–5]. Establishing and managing protected areas is, thus, one of the most important policy tools for achieving environmental, natural resource conservation and climate goals. Following this premise, the United Nations Convention on Biological Diversity [6] recommends each country establish and manage protected areas to conserve biological diversity. The United Nations 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) recognize protected areas as a key strategy for biodiversity conservation and sustainable development in the targets they contain, such as the Aichi Biodiversity Target 11, SDG goals 14 and 15 [7]. Furthermore, an opportunity was presented for conservation of tropical forests through the United Nations Climate Agreement [8] on reducing emissions from deforestation and degradation, plus forest management and conservation, and enhancement of carbon stock (REDD+). Therefore, the most important immediate steps to achieve these goals include intensive conservation of existing protected areas, establishing additional conservation areas of tropical forests, and supporting areas of high conservation benefits in terms of carbon, biodiversity and other ecosystem services.

The United Nations [9] records more than 200,000 protected areas worldwide, of which 840 are in Tanzania. Tanzania indeed devoted a sizeable proportion of its land area (36%) for conservation, with an original goal of conserving forests, landscapes and wildlife. PAs in Tanzania are currently managed most commonly by the central government or local authorities, either as Forest Reserves, Game Controlled areas, Game Reserves, National Parks, Nature Reserves, Village Forest Reserves or Forest Plantations. Tanzanian PAs include some UNESCO world heritage sites such as the Kilimanjaro and Serengeti National Parks, Selous Game Reserve and Ngorongoro Conservation Area; and series of PAs with exceptional endemism along the Eastern Arc Mountains. Tanzanian PAs are generally regarded as biodiversity hotspot, with over 10,000 plant species, hundreds of which are nationally endemic. Of the plant and animal species, 724 are identified as "threatened" in the Red List of the International Union for Conservation of Nature (IUCN), with 276 species classified as "endangered" [10].

Other than biodiversity conservation, PAs in Tanzania are offering an increasingly diverse set of ecosystem services. Among them is the significant contribution to the national economy through tourism revenues, most popular of which is ecotourism, involving natural environments and wildlife, through which Tanzania remained the best safari destination in Africa. As a result, Tanzania's tourism sector is one of the most significant income earners. Furthermore, the sheer size (total area) and the large number and diversity of PAs in Tanzania means that their role in mitigation to climate change through carbon sequestration, and thus the potential to garner financial benefits, is enormous.

Deforestation caused by human activities such as agricultural expansion, charcoal production and illegal logging inside and within the buffer areas can undermine the ecosystem and climate benefits of PAs. Deforestation in buffer areas further undermines the connectivity among PAs, and thus lead to isolation [11], which in turn can potentially cause restriction of the ability of plant and animal species to relocate to new geographic areas as well as changing plant community structure and diversity within PAs because of herbivore concentration [12]. Consequently, conservation and connectivity of PAs have international significance as the Aichi Target 11 of the Convention on Biological Diversity demands countries have at least 17% of the land covered by well-connected PA systems by 2020 (IUCN). The Millennium Ecosystem Assessment [13] has long identified deforestation as the primary driver of biodiversity loss. Therefore, reducing deforestation and improving the connectivity of PAs play fundamental role to ensure species survival, particularly in the context of habitat protection. Habitat fragmentation and isolation that can be caused by anthropogenic activities obstruct the possibility for genes and species to move amongst protected areas [14].

Annual deforestation in Tanzania was close to 470,000 ha between 2002 and 2013 [15], which constitutes a significant contribution of the total anthropogenic emissions from the land-use change in the country. These would provide the theoretical basis for strengthening the protection of existing conservation areas, allocating additional areas of conservation and improving the connectivity of PAs. Tanzania acknowledges deforestation as a major threat to biodiversity and ecosystem services, and is committed to most of the targets in the Convention on Biological Diversity [16]. This includes a commitment to effectively manage existing protected areas (Target 11), and to significantly reduce the rate of degradation and fragmentation of ecosystems and the loss of habitats (Target 5). However, forest cover loss due to deforestation inside PAs and in their external buffer areas are often not objectively quantified and analyzed, particularly given the vast size and number of PAs in Tanzania. Studies that quantify deforestation inside of PAs and assess connectivity and isolation would be useful to understand the climate change mitigation potentials and the conservation benefits of PAs.

This study draws on the best available Landsat based remote sensing data of forest cover change for the period 2002–2013, to assess deforestation within PAs and their external buffer areas in Tanzania. The specific objectives are (1) to evaluate deforestation inside and within the buffer areas of PAs, (2) evaluate connectivity between PAs, the lack of which can potentially lead to isolation, and (3) whether and to what extent deforestation among PAs vary by PA management regimes.

2. Data and Method

2.1. Study Area

The study area covers the mostly centrally managed PAs and those located in mainland Tanzania where they are collectively known as Conservation Areas. These are sub-grouped based on management regimes as National Parks (NP), Game Reserves (GR), Game Controlled (GC) areas, Nature Reserves (NR), Forest Reserves (FR), and Forest Plantations (FP) (Figure 1). General characteristics of the management regimes are summarized in Table 1. We excluded PAs designated as village forest reserves and wildlife management areas, due to inadequate spatial coverage data and lack of accurate shape polygons. In addition, we also removed 48 small PAs (area = 0–10 ha) located either on islands or mostly mangroves near the cost as they were not adequately covered by either the shape files or the deforestation map. Additional areas that are excluded from the analysis include buffers overlapping with water bodies or territories of other countries. The study finally included 708 PAs covering a total area of nearly 31 million ha and their corresponding unprotected buffer areas of more than 60 million ha within a range of 0–10 km surrounding each PA.

Table 1. Characteristics of the six Protected Area (PA) management regimes in main land Tanzania.

PA Management Regimes	Number of PAs	Management Regime Total Area (1000 ha)	Managing Authority
Forest plantations	23	73	Tanzania Forest Services
Forest Reserves	625	9316	Tanzania Forest Services
Game Controlled Areas	19	7101	Tanzania Wildlife Management Authority
Game Reserves	19	9426	Tanzania Wildlife Management Authority
National Parks	16	4851	Tanzania National Parks Authority
Nature Reserves	6	200	Tanzania Forest Services
Total	*708*	*30,967*	Tanzania, National

2.2. Data

PA polygons: we obtained data for the location and boundary polygons of the 708 PAs from the World Database for Protected Areas (WDPA) updated January 2019 [17], managed by the United Nations Environment World Conservation Monitoring Centre (UNEP-WCMC) with support from IUCN and its World Commission on Protected Areas (WCPA) (Protectedplanet.net).

Deforestation data: we extracted data for 11 years (2002–2013) of deforestation area for all PAs and their buffer areas from a wall-to-wall deforestation map of Tanzania, developed for the purpose of Forest Reference Emission Level (FREL) of Tanzania (FREL) [15]. The wall-to-wall deforestation map was developed from changes from Landsat 7 Enhanced Thematic Mapper Plus (ETM+) (2002) to Landsat 8 Operational Land Imager (OLI) (2013), covering the entire mainland Tanzania. The deforestation map used a total of 85 Landsat 7 ETM+ (2002) and Landsat 8 (2013) images, with a resolution of 30 m. The Landsat 7 ETM+ scenes were pre-processed by the USGS to surface reflectance level using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) atmospheric and topographic correction algorithm. The Landsat 8 scenes were pre-processed to surface reflectance level by the United States Geological Survey USGS internal L8SR algorithm.

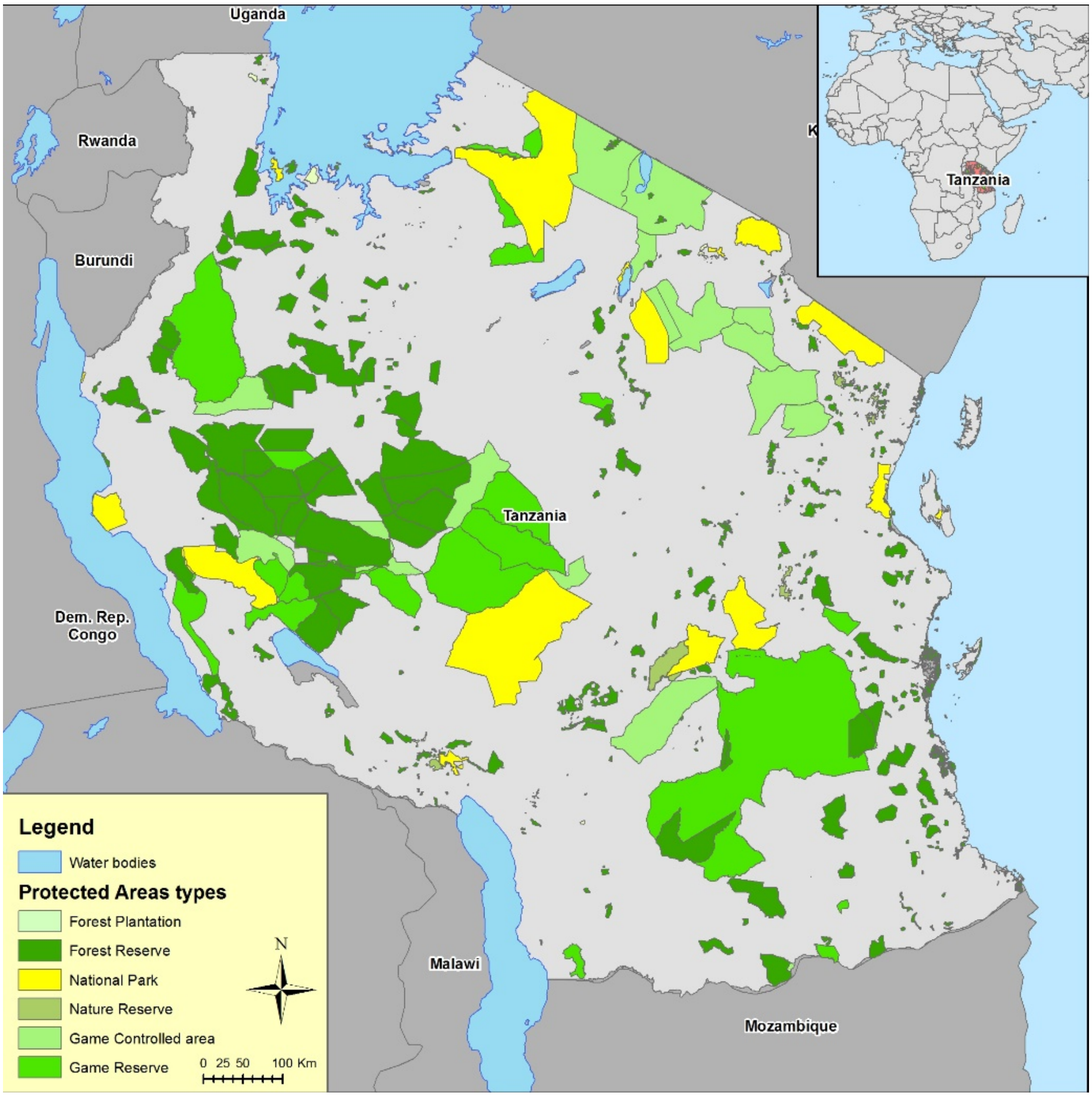

Figure 1. Location of Tanzania in Africa and Protected Areas (PAs) in Tanzania by management regimes. The different colors (except the blue which are water bodies) represent management regimes, namely (in no particular order), National Parks (NP), Game Reserves (GR), Game Controlled (GC) area, Nature Reserves (NR), Forest Reserves (FR), and Forest Plantations (FP).

The advantage of the wall-to-wall deforestation data used here over other change maps such as Global Forest Watch include, (1) Forest definition used for classification was based on predetermined national forest definition based on forest area (at least 0.5 ha), crown cover (at least 10%) and potential tree height (at least 3 m); (2) the land-use classification was monitored and evaluated by expertise with knowledge of the area, and (3) the accuracy of the deforestation map was evaluated using a combination of the National Forest Inventory (NAFORMA) plot data of the 2010 and the Regional Centre for Mapping and Resource Development (RCMRD) Land use land cover map of Tanzania.

We extracted deforestation data as land-cover change from forest to non-forest (ha) for all PAs for the period 2002–2013. We also extracted deforestation data for pairs of internal and external buffers in concentric bands of 0–0.5 km, 0.5–1 km, 1–5 km and 5–10 km measured from the boundary of each PA. Internal buffers here after refer to areas just inside the boundaries of the PAs towards the center of the PAs, while external buffers refer to areas just outside the boundaries of the PA. For the construction of the concentric bands in the external buffer zones, areas that fall either on another PA, water bodies, or outside of the territories of Tanzania were excluded. For those PAs where the internal concentric bands were not possible to construct (i.e., size of the PA smaller than the concentric band area), the deforestation for that concentric band was estimated as the deforestation of the entire PA. Where PAs overlap, the areas are merged for total area estimation. Figure 2 shows the work flow in ArcGis on the simultaneous construction of concentric bands, and extraction of data on each PA and its corresponding concentric bands from the deforestation data, and thweir export to a worksheet. In the absence of data from field observation or measurements of the period, only visual validation was made using independent images from space imagery providers including Google Earth, Environmental Systems Research Institute (ESRI) and DigitalGlobe for selected PAs and buffer areas.

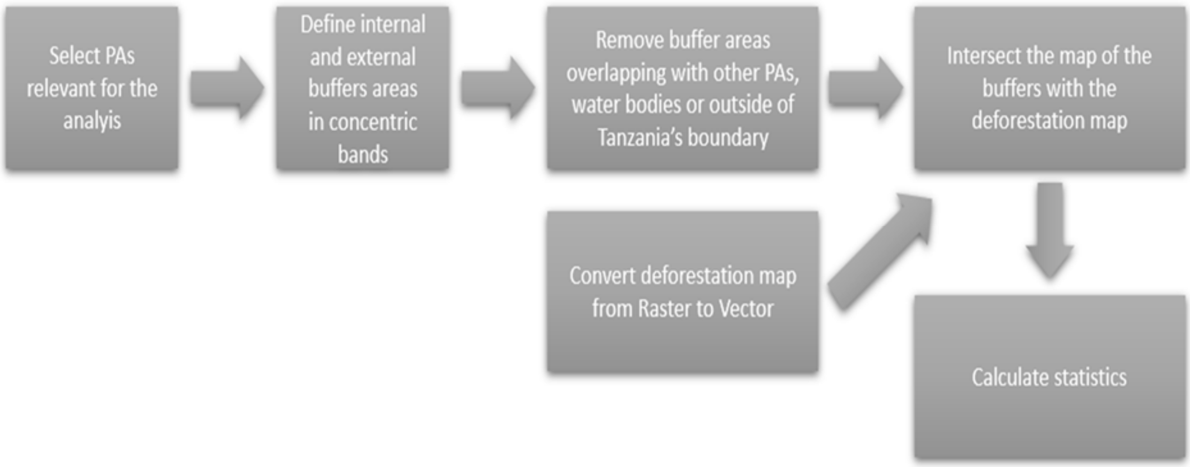

Figure 2. Work flow diagram in ArcGis for the simultaneous construction of concentric bands and extraction of data and output to worksheet.

2.3. Statistical Analysis

Deforestation inside and within the buffer areas of PAs: deforestation was defined as an area converted from forest to non-forest (ha) within each PA and estimated as the sum of the areas of individual pixels with forest-to non-forest conversion during the period 2002–2013. Proportion of the area deforested was then estimated as (a) the ratio of the area deforested to the total area of the PA, which indicates the absolute forest to non-forest conversion rate; and (b) the ratio of the area deforested to the total area of the forest within the PA at the beginning of the monitoring period, which indicates the relative forest to non-forest conversion rate. Further, proportion of the area deforested within each buffer area was calculated as the ratio of area deforested within the given concentric band (0–0.5; 0.5–1; 1–5; 5–10 kms) divided by the area of that concentric band. The metric allows pairwise comparisons and correlations analysis between the rates of deforestation inside the boundaries and that of unprotected buffer areas.

Connectivity and isolation of PAs: given the lack of indicators or quantitative criterion to define connectivity or the lack of it (isolation); we identified PAs surrounded by unprotected landscapes, and no connection to the neighboring PA(s) within at least 1 km from their boundaries. We identified such PAs as "isolated" and assessed their unprotected external buffer areas for deforestation in an increasing distance within 0–0.5; 0.5–1; 1–5; 5–10 km from their boundaries. Pairwise *t*-test and correlation analysis were used between deforestations inside boundaries of isolated PAs and the corresponding buffer areas with increasing distances to assess the pressure of activities outside the PA boundaries on the corresponding PAs.

PA management effects: we used the generalized linear model (GLM) for the analysis of variance (ANOVA) to test the variations in deforestation among the six PA management categories (FP, FR, GC, GR, NP, and NR). Since there is a considerable size variation among the PAs, the GLM considered the area-weighted mean. An alternative approach was an ANOVA accounting for PA management, PA size, and PA management by PA size interaction, but this produced the same results and thus the latter was omitted. Following ANOVA, the Duncan's multiple range test was used to compare the area-weighted mean deforestation among the six management categories. PA size effects entered the analyses by dividing PAs into three size-based cohorts. After preliminary tests, three percentile-based cohorts were found to be sufficient. These are PAs with size less than or equal to the 25th percentile (Q1); PAs that are larger than the 25 percentile and less than or equal to the 75 percentile (Q2); PAs that are larger than the 75th percentile (Q3). These cohorts were further used to test whether PAs in the smaller cohorts are disproportionately deforested than those in the larger cohorts.

3. Results

3.1. Deforestation inside Protected Areas (PAs) and the Buffer Areas

Annual deforestation averaged 140 422 (STD = 922) ha during 2002–2013, which in absolute terms amounts to 5% of the total land area of all PAs combined. The corresponding annual forest loss within the PAs was about 0.8%. At the individual PA level, deforestation varied widely among PAs. About 23% (n = 160) of the PAs received effective and fortress type protection and thus no deforestation. This includes most National Parks and series of Forest Reserves, such as PAs along the Usambara Mountains (Figure 3). In contrast, some PAs have lost more than 50% of their forested areas during the same period (e.g., Makere South Forest Reserve). Deforestation was rather concentrated in few, larger PAs. A small proportion (10%, n = 71) of the PAs contributed more than 90% of the total deforestation during the monitoring period. However, in terms of land area, these 71 PAs represent 77% of the total protected areas. Inside deforested PAs, more deforestation in general occurred near the periphery of their boundaries than the interior. Comparing deforestation rates in the inside peripheries of PAs and their external buffer areas, 51% (n = 359) of the 708 PAs exhibited significantly lower deforestation rates. Table 2 summarizes the characteristics of deforestation among PA management regimes. Figure 3 visually demonstrates selected PAs representing highly protected and highly deforested PAs; and Figure 4 contrasting protection inside and the buffer areas.

Table 2. Summary of PA characteristics: number and size of PAs, total 11 years (2002–2013) deforestation (ha), and area deforested as percentage of PAs total management area, and PA forest area at the beginning of monitoring period.

PA Management Regime	Deforestation (ha)	Deforestation, Percent of Forested Area within PA	Deforestation, Percent of the Management Area
Forest plantations	875	1.4	1.2
Forest Reserves	806,544	12.6	8.6
Game Controlled Areas	432,280	13.4	6.1
Game Reserves	267,060	5.4	2.8
National Parks	37,875	2.2	0.78
Nature Reserves	446	0.2	0.22
Total	*1,545,080*	*9.3*	*5*

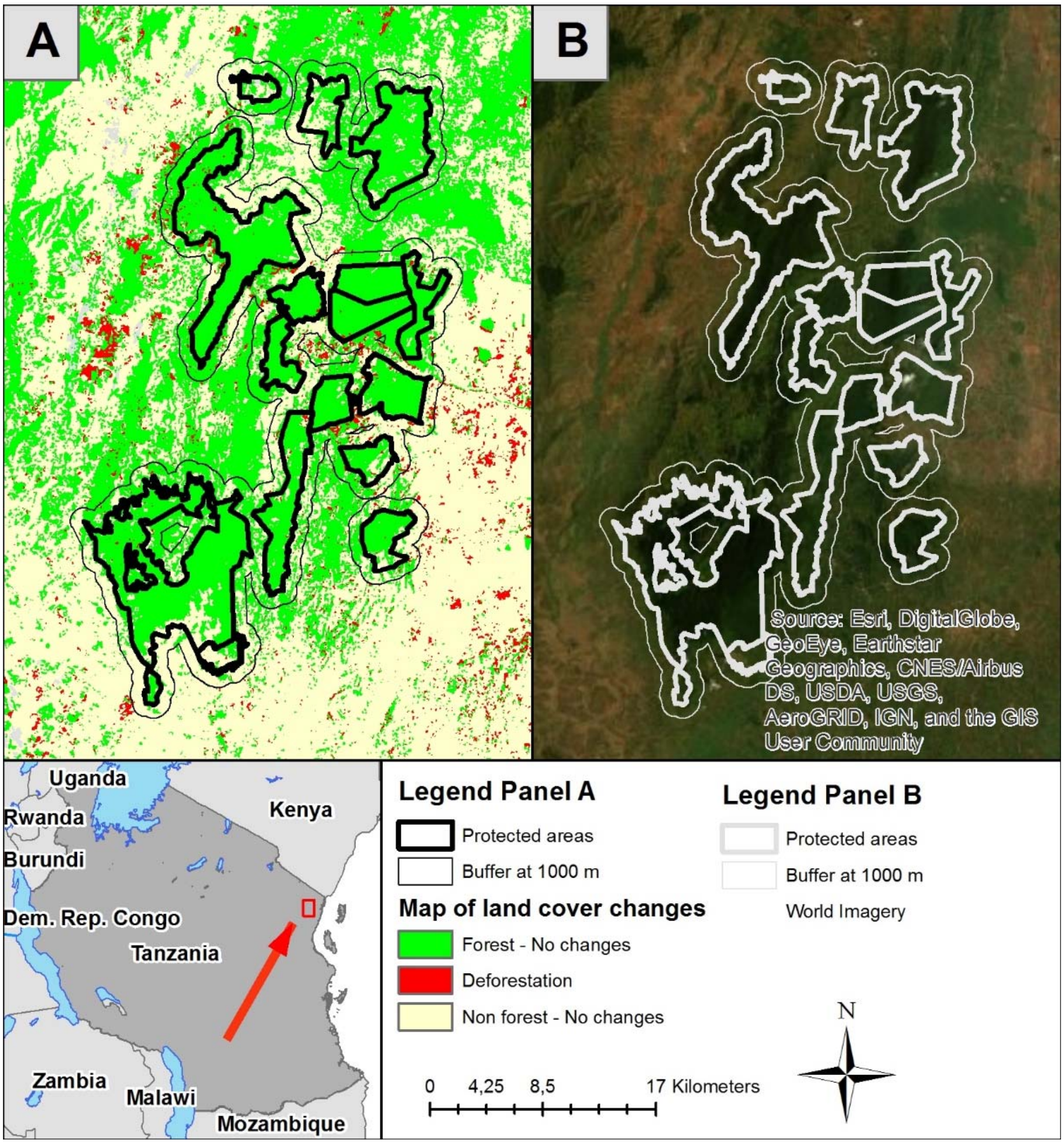

Figure 3. Series of PAs along the Usambara Mountains of northeastern Tanzania along the eastern most ranges of the Eastern Arc Mountains. Note: effective protection with few spots or no deforestation inside and the buffer areas of the PAs. The buffer area in the figure is 1 km non-overlapping zone surrounding the PA network. Panel (**A**) is. of this study; and Panel (**B**) is image from space imagery providers.

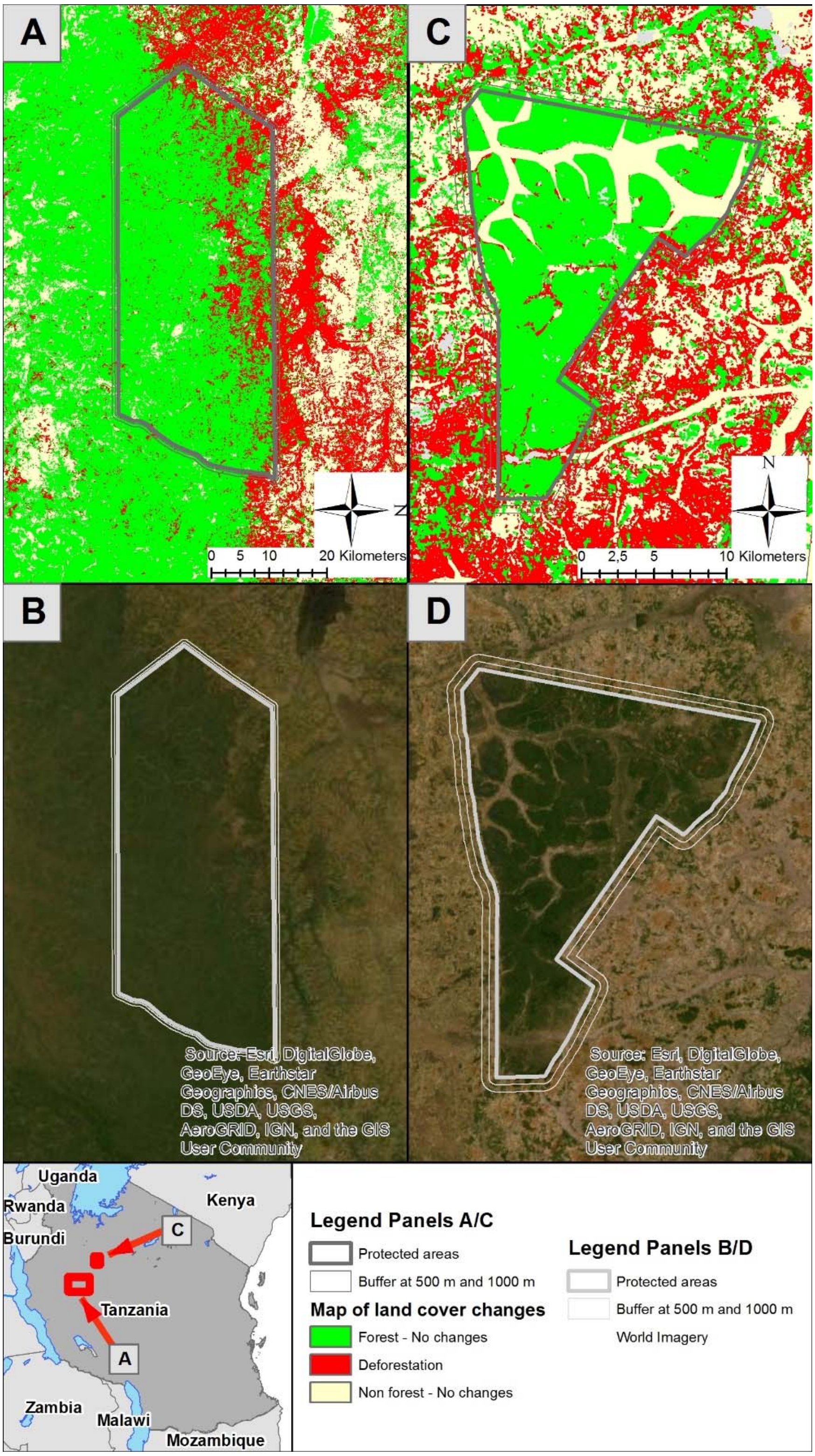

Figure 4. Example of PAs with negligible deforestation inside their boundaries (Panels (**C**,**D**), Karitu Forest Reserve) and with a sizeable and advancing deforestation inside the boundary (Panels (**A**,**B**); Ugala North Forest Reserves), in western Tanzania.

3.2. Connectivity and Isolation of PAs

The analysis on connectivity showed that 352 PAs are at least 0.5 km away from their neighboring PAs while 293 PAs are at least 1 km away from the nearest PA. In terms of management regime, these isolated PAs mostly belong to the Forest Reserves, consistent with their higher number among the different regimes. In general, in the buffer areas of PAs, deforestation rates were lower in areas closer to the external boundaries (in the buffer zone 0–1 km) than those further away, e.g., in the buffer zones 5–10 km (e.g., Figures 5 and 6). Deforestation in buffer areas as percent of the unprotected buffer areas in a range of 0–10 km was estimated at 7%. We found a strong and positive correlation ($p < 0.0001$) between deforestation inside the boundaries and deforestation in the buffer areas, although declining with distance. Figure 5 shows two isolated PAs (Matogoro West and Matogoro East), where deforestation inside is highly correlated with deforestation in the outside buffer areas. A series of PAs across Tanzania, for example those located along the central part of the Eastern Arc Mountains, shows evidence of lack of connectivity, which we defined as an indicator of isolation (Figure 6).

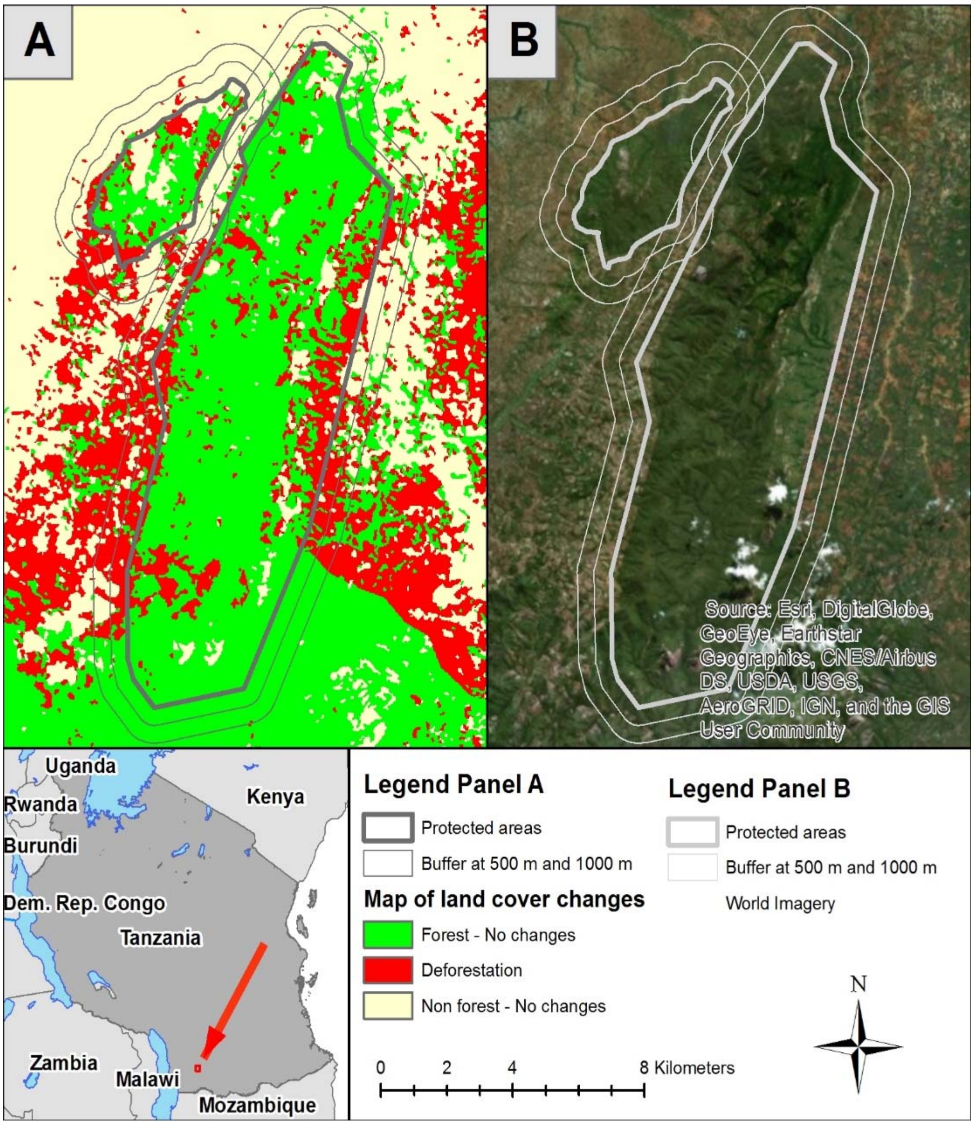

Figure 5. Deforestation in the buffer areas of two isolated PAs (Forest Reserves of Matogoro West and Matogoro East), Southern Tanzania. Panel (**A**) is of this study; and Panel (**B**) is image from space imagery providers.

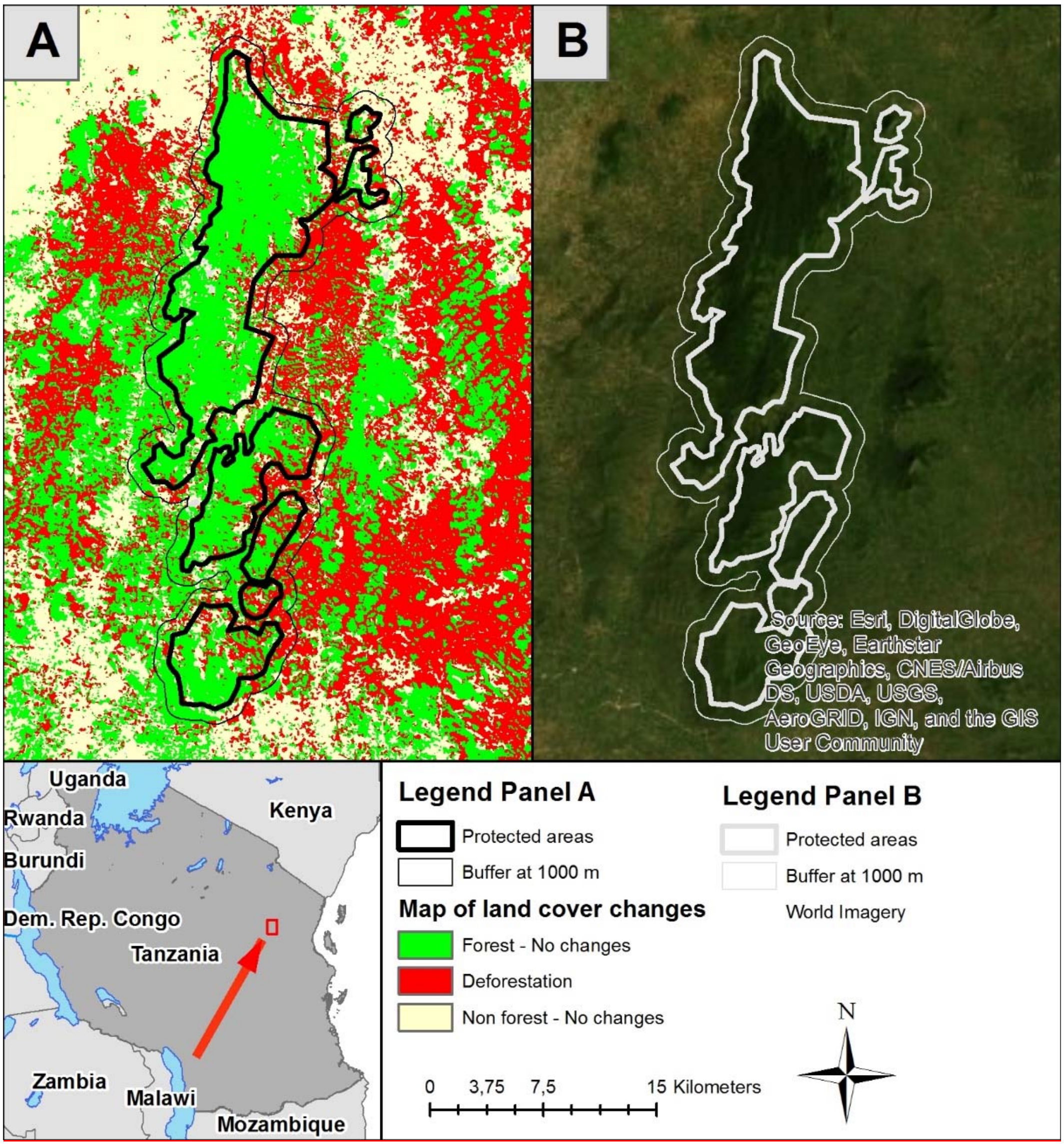

Figure 6. Deforestation inside and the buffer areas of mostly disconnected PAs (Forest Reserves) along the Eastern Arc mountains in Eastern Tanzania. PAs in figure are (North to South): Nguru North, Mamboto, Mkongo, Nderema, Pumula, Mbwegere, and MKuli Forest Reserves. Panel (**A**) is. of this study; and Panel (**B**) is image from space imagery providers.

3.3. PA Management Effects

Results of analysis of variance (ANOVA) revealed that the differences in area-weighted mean deforestation among PA management regimes are significant ($p < 0.0001$). An alternative ANOVA that considered PA management categories, PA size and interaction effects also revealed significant ($p < 0.0001$) management, size and interaction effects. Following ANOVA, the results of Duncan's means grouped the six management categories into three. Game Controlled Areas presented the highest area-weighted mean annual deforestation; followed by Forest Reserves, Game Reserves and National Parks; while Forest Plantations, and Nature Reserves exhibit the lowest (Figure 7). Therefore, most of the deforestation in Tanzanian PAs during the period occurred in Game Controlled Areas and Forest Reserves. However, this does not mean that deforestation is high in all Game Reserves or Forest Reserves; given the large variations within protection status of same management regime (Figure 7). The percentage of deforestation during the entire 11 years (deforestation as percent of total PA area) is the highest in Forest Reserves, followed by the Game Controlled areas while the lowest was in Nature

Reserves. Controlling management effects, deforestation was significantly small for the lowest size cohort (Q1) ($p < 0.05$), while there is no significant difference between the median (Q2) and the higher cohort (Q3).

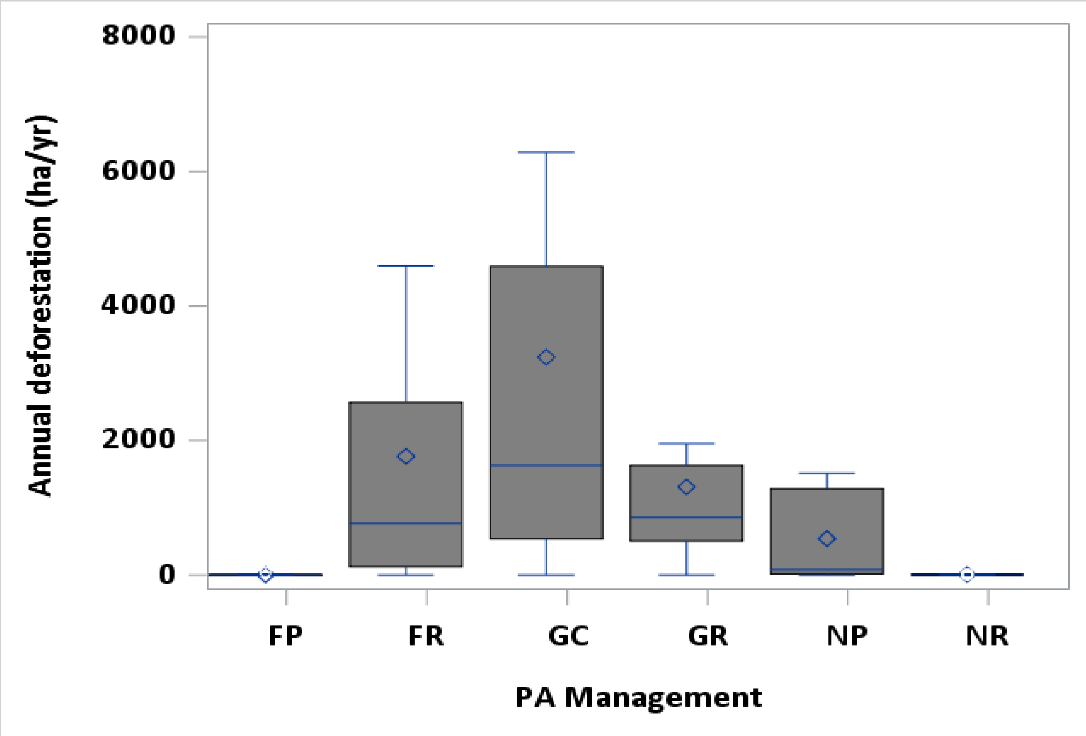

Figure 7. Area-weighted annual deforestation rates (ha/yr) in protected areas of Tanzania (*n*/; = 708) and the six PA management regimes namely Forest Plantations (FP), Forest Reserves (FR), Game Controlled areas (GC), Game Reserves (GR), National Parks (NP) and Nature Forest Reserves (NR).The central notched line is the median, and the diamonds are the area-weighted mean; and the whiskers are the lower and the upper confidence limit.

4. Discussions

4.1. Deforestation and Isolation of PAs

The estimated annual deforestation rate of 0.45% among PAs during the 11 years of the monitoring period is a significant reduction compared to an estimated annual deforestation rate of 0.63% for the unprotected buffer areas. This is further strengthened by the finding that two-thirds of the PAs have significantly less deforestation than the surrounding landscapes, including those with no or negligible deforestation inside their boundaries. This includes some of the famous National Parks and Nature Reserves with little or no deforestation, being inaccessible and fortressed. This suggests PAs have contributed in reducing the otherwise ferocious annual deforestation rate of 0.7% in Tanzania during the same period, 2002–2013 [15]. Therefore, protection can be an effective strategy for reducing deforestation, consistent with some recent studies [18]. These relatively well protected PAs represent 22% of the land area of Tanzania; meaning Tanzania has already succeeded in achieving the 17% target of its territory as protected defined by the Convention on Biological Diversity [16]. This demonstrates Tanzania's commitment to conservation as a signatory of major international biodiversity treaties, and by implementing domestic conservation laws and regulations enshrined in the National Forest Act of 2002.

However, our results showing some PAs that are deforested as much as the unprotected buffer areas and some that have lost up to 50% of their forested area during the 11 years indicates that not all PAs received similar protection status. This is common in a number of rainforest areas and regions with large number of protected areas, where protection resulted in mixed outcomes in terms of reducing deforestation [2,3,5,19–22]. Uniquely for Tanzania, however, only few large PAs (n = 75) represent the great majority (>90%) of deforestation. These highly deforested PAs should remain a management concern, because despite their number, they represent more than two thirds of the protected area in Tanzania in terms of size.

On the other hand, more than 50% of Tanzanian PAs are well connected to one or more neighboring PAs, particularly those in western Tanzania connected to Katavi national park and those in the south western Tanzania surrounding the Selous Game reserve (Figure 1). This makes Tanzania one of the few countries fulfilling the Aichi Target of "well-connected" PAs [16]. While these results may be encouraging, we also found the remaining half, most of which are Forest Reserves (371 Forest Reserves), are isolated by at least 0.5 km, often surrounded by land use or landcover other than forests. Other studies [18,23] showed that unprotected landscapes adjacent to many protected areas have been converted to other land uses. In many cases, isolation becomes the reason for deforestation to push into the boundaries of PAs, threatening the effectiveness of PAs to maintain viable forest and protect biodiversity in the long term [14].

The significantly strong correlation between deforestation in the buffer areas and deforestation inside PAs shown in this study suggests that PAs are being influenced by human activities outside their boundaries. In particular, Forest Reserves and Game Controlled areas that are located near or inside of human dominated landscapes are subject to isolation. For instance, PAs along the Eastern Arc mountains are known for exceptional biological and conservation importance but have long been threatened by deforestation [24,25]. Our observation corroborates these previous reports, albeit the different monitoring periods, that large parts of the buffer areas of many PAs along the Eastern Arc Mountains were deforested (e.g., see Figures 5 and 6) or isolated, although well protected (Figure 3) which, in the absence of intervention, can potentially lead to further isolation and encroachment into PA territories, threatening the ecosystem services they can provide. Nevertheless, the potential for connecting those isolated PAs is immense, because most are located within short distances from each other. For instance, along series of PAs in the Usambara Mountains of northeastern Tanzania (Figure 3), developing a 1 km corridor surrounding each PA can effectively connect nearly all protected areas in that mountain range. Indeed, as shown in Figure 3, effective protection inside PAs might have prompted protection across the unprotected buffer zones surrounding those PAs. Remaining governance challenges could be designing and implementing compensation schemes for conservation-related displacements of people in buffer areas and sometimes inside PA territories [26].

4.2. PA Management Effects

Knowledge on the degree to which responsible public institutions can protect their respective natural forests and biodiversity will have a profound importance to the public and Tanzanian decision makers. At the level of PA management, Forest plantations, National Parks and Nature Reserves exhibit significantly less deforestation rate than Forest Reserves and Game Controlled areas (see also Figure 7). These results are strikingly similar to that of Uganda [22], in which Forest Reserves lost forest carbon while National Parks and wildlife Reserves gained forest carbon during 10 years monitoring period. Another study in East Africa [27] suggested that the other management regimes performed poorly as compared to National Parks in reducing deforestation. National Parks and Nature Reserves may have better protection status than Forest Reserves, most likely because they benefit from inaccessibility and fortress-type protection assisted by tourism revenues to support and strengthen protection. While these are generalized conclusions, we also see that there is a large variation in protection status within the same management regime (Figure 7). For instance, while Forest Reserves in general were deforested, there are a series of Forest Reserves, for instance in Eastern Usambara Mountains in northeastern Tanzania that are well protected and showed no or little deforestation during the period. This result is of significance because the Usambara mountains make up the Eastern Arc forests which have the highest known number of plant and animal species of any region in Tanzania.

The observed deforestation, particularly in the top 10% highly deforested PAs dominated by Forest Reserves is most likely attributed to their location leading to an increasing external pressure associated with the increasing human population in the surrounding landscapes. Giliba et al., [28] suggested that the threat against Forest Reserves is well connected to an increasing demand for household energy and the need for new land for cultivation and settlements near population areas. Visual observations show that even when PAs are well protected, they may be surrounded by recently deforested landscapes (e.g., see Figures 4–6). Such fortress-type protection may cause leakage (spillover) to neighboring buffer areas [29], and that leakage might accelerate the rate at which PAs become isolated [23]. Therefore, PA management need to consider the potential of leakage. However, given the limited field observation, and lack of histories of the PAs on their establishment, we could not ascertain whether leakage was responsible for the observed isolations in Tanzanian PAs.

PAs may be established purposely in dense forests, higher elevations, steeper slopes or long distances to roads and settlements, particularly those that have been established many years ago. Our comparison between changes inside the boundaries and the buffer areas did not consider the possible differences in land characteristics and possible biases of locations during the establishment of these PAs. However, with a current expanding infrastructure and fast-growing young population demanding agricultural land, most of the PAs are within the reach of human activities. Some of the urgent measures for management authorities and other stakeholders should therefore include reviewing existing management approaches, to consider participatory management which promotes partnerships and offers benefit sharing and other development opportunities to communities living outside PAs. Successful practices of engaging local communities exist in Tanzania and experiences can be drawn from the past participatory forest resource-management programs [30], and carefully adapted to serve PA management objectives.

4.3. Implications for the Climate Benefits of Protection

Protection in Tanzania has historically been intended for ecosystem services, such as ecotourism and biodiversity conservation. More recently, the Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change (UNFCCC) [8] entails low greenhouse gas emissions and climate-resilient development. In particular, policies such as REDD+ recognized conservation as one of the five major activities [8], providing additional opportunity for PAs. More specifically, Tanzania's recent Climate Smart Agriculture (CSA) guideline [31] recognizes landscape and ecosystem services and payments for ecosystem services as key to achieving its sustainable development goals. Furthermore, as part of its commitment under African Forest Landscape Restoration (AFR100) initiatives, in 2018 Tanzania pledged to restore 5.2 million hectares of degraded and deforested land by 2030. Tanzania can thus use this opportunity to select those buffer zones or corridors as restoration areas under such programs.

Given the large sizes and diversity of PAs, protection in Tanzania can make significant and vital contributions to emissions reduction. This study also provided evidence that strictly protected PAs are effective at reducing forest losses and thus reducing emissions. However, protection is particularly challenging and resource-intensive in countries such as Tanzania, with high forest dependence where forest-based charcoal and fuel wood are the single most important sources of household energy [32], and forest lands provide the last remaining lands for agricultural expansion [33].

Initiatives such as REDD+ and other national forest-management strategies are expected to provide a solution through providing incentives for the respective authorities and to the local communities. Consequently, Tanzania can benefit from PA managements as a national strategy and policy options to achieve its climate goals, through reducing emissions from deforestation and forest degradation inside the PAs. Protection should also consider the buffer areas through, for instance, initiating actions to restore and develop unprotected areas into corridors, through initiatives such as promoting community forest reserves, landscape restoration and conservation agriculture, and improving the connectivity of isolated PAs. Improving connectivity requires strong cooperation and partnership between the different PA management regimes, developing approaches on how communities living adjacent to PAs can participate and share the benefits. Community engagement and benefit sharing can avoid the pitfalls of the current management in which several Forest Reserves appear isolated, surrounded by deforested or landscapes.

5. Conclusions

This study provided a quantitative assessment of deforestation in all the major PAs and their corresponding buffer areas across six PA management regimes in Tanzania. Such knowledge will contribute to understanding of the conservation and the climate change mitigation potentials of PAs. We see that the outcomes of protection in Tanzania are generally mixed, ranging from fortress-type protection with no deforestation detected to those PAs where protection did not significantly reduce deforestation. Yet, most PAs in Tanzania have been effective in reducing deforestation, despite the significant land-use pressure from outside their territories. This provides considerable support to the notion that protection remains one of the most effective policy tools to reduce deforestation, and thus protecting valuable landscapes and biodiversity, conforming to the original goal of protection. These results also demonstrate the potential that PAs can offer a considerable opportunity to achieve long-term climate goals such as the nationally determined contributions (NDCs) and climate mechanisms such as REDD+.

Despite successes in some PAs across the different management regimes, there is a clear need to strengthen protection of the few but large-area PAs with high deforestation rates and promoting connectivity of many isolated PAs through forest landscape restoration and developing corridors. The challenges are often designing and implementing win-win solutions both for the PA management and communities that can be affected by conservation. Successful participatory forest management programs that engage communities exist in Tanzania, from which experiences can be drawn and adapted to PA management.

We demonstrated the utility of a wall-to-wall land-cover change map to monitor deforestation inside PAs and the unprotected buffer areas at various distances. Given the dynamics of deforestation in Tanzania, however, there is a need for updated data and supplementary field observation to improve the utility of such data and assessments for a more assertive recommendation.

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References

1. Spracklen, B.D.; Kalamandeen, M.; Galbraith, D.; Gloor, E.; Spracklen, D.V. A Global Analysis of Deforestation in Moist Tropical Forest Protected Areas. *PLoS ONE* **2015**, *10*, e0143886. [CrossRef] [PubMed]
2. Pfaff, A.; Robalino, J.; Herrera, D.; Sandoval, C. Protected Areas' Impacts on Brazilian Amazon Deforestation: Examining Conservation—Development Interactions to Inform Planning. *PLoS ONE* **2015**, *10*, e0129460. [CrossRef] [PubMed]
3. Forrest, J.L.; Mascia, M.B.; Pailler, S.; Abidin, S.Z.; Araujo, M.D.; Krithivasan, R.; Riveros, J.C. Tropical Deforestation and Carbon Emissions from Protected Area Downgrading, Downsizing, and Degazettement (PADDD). *Conserv. Lett.* **2015**, *8*, 153–161. [CrossRef]
4. Collins, M.B.; Mitchard, E.T.A. A small subset of protected areas are a highly significant source of carbon emissions. *Sci. Rep.* **2017**, *7*, 41902. [CrossRef]

5. Blankespoor, B.; Dasgupta, S.; Wheeler, D. Protected areas and deforestation: new results from high-resolution panel data. *Nat. Resour. Forum* **2017**, *41*, 55–68. [CrossRef]
6. UN. Convention on Biological Diveristy. 1992. Available online: https://www.cbd.int/doc/legal/cbd-en.pdf (accessed on 28 June 2017).
7. UNEP. Protected Planet Report 2016: Data, Maps & Figures (April 2016). Available online: https://www.protectedplanet.net/c/protected-planet-report-2016/protected-planet-report-2016--data--maps-figures (accessed on 8 March 2019).
8. UNFCCC. Adoption of the Paris Agreement. Draft decision -/CP.21. Conference of the Parties Twenty-first session Paris, 30 November to 11 December 2015. Available online: http://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf (accessed on 29 December 2015).
9. UNEP-WCMC, United Nations List of Protected Areas. *Supplement on protected area management effectiveness*; UNEP-WCMC: Cambridge, UK; Available online: https://www.sprep.org/attachments/VirLib/Global/2018-list-protected-areas.pdf (accessed on 8 August 2019).
10. IUCN. *IUCN Red List of Threatened Species. Version 2013.01*; IUCN: Gland, Switzerland, 2013; Available online: www.iucnredlist.org/ (accessed on 12 June 2017).
11. Bailey, D.; Schmidt-Entling, M.H.; Eberhart, P.; Herrmann, J.D.; Hofer, G.; Kormann, U.; Herzog, F. Effects of habitat amount and isolation on biodiversity in fragmented traditional orchards. *J. Appl. Ecol.* **2010**, *47*, 1003–1013. [CrossRef]
12. Griffen, B.D.; Drake, J.M. Effects of habitat quality and size on extinction in experimental populations. *Proc. R. Soc. B Boil. Sci.* **2008**, *275*, 2251–2256. [CrossRef]
13. Steve, P.; Jane, L. *Millennium Ecosystem Assessment, Ecosystems and Human Well-Being: Biodiversity Synthesis*; World Resources Institute: Washington, DC, USA, 2005.
14. Newmark, W.D. Isolation of African protected areas. *Front. Ecol. Environ.* **2008**, *6*, 321–328. [CrossRef]
15. The United Republic of Tanzania, TANZANIA'S FOREST REFERENCE EMISSION LEVEL SUBMISSION TO THE UNFCCC. 2017. Available online: https://redd.unfccc.int/files/frel__for__tanzania_december2016_27122016.pdf (accessed on 7 January 2019).
16. UNEP, Convention on Biological Diversity. 2010. Available online: https://www.cbd.int/nbsap/targets/ (accessed on 27 November 2019).
17. UNEP-WCMC. Protected Planet 2014–2019. 2019. Available online: https://www.protectedplanet.net/search?q=Tanzania (accessed on 1 February 2019).
18. Bowker, J.N.; Vos, A.; Ament, J.M.; Cumming, G. Effectiveness of Africa's tropical protected areas for maintaining forest cover. *Conserv. Boil.* **2017**, *31*, 559–569. [CrossRef]
19. Rodriguez, N.; Armenteras, D.; Retana, J. Effectiveness of protected areas in the Colombian Andes: deforestation, fire and land-use changes. *Reg. Environ. Chang.* **2013**, *13*, 423–435. [CrossRef]
20. Eklund, J.; Blanchet, F.G.; Nyman, J.; Rocha, R.; Virtanen, T.; Cabeza, M. Contrasting spatial and temporal trends of protected area effectiveness in mitigating deforestation in Madagascar. *Boil. Conserv.* **2016**, *203*, 290–297. [CrossRef]
21. Cuenca, P.; Arriagada, R.; Echeverría, C. How much deforestation do protected areas avoid in tropical Andean landscapes? *Environ. Sci. Policy* **2016**, *56*, 56–66. [CrossRef]
22. Gizachew, B.; Solberg, S.; Puliti, S. Forest Carbon Gain and Loss in Protected Areas of Uganda: Implications to Carbon Benefits of Conservation. *Land* **2018**, *7*, 138. [CrossRef]
23. Lui, G.V.; Coomes, D.A. Tropical nature reserves are losing their buffer zones, but leakage is not to blame. *Environ. Res.* **2016**, *147*, 580–589. [CrossRef] [PubMed]
24. Hall, J.; Burgess, N.D.; Lovett, J.; Mbilinyi, B.; Gereau, R.E. Conservation implications of deforestation across an elevational gradient in the Eastern Arc Mountains, Tanzania. *Boil. Conserv.* **2009**, *142*, 2510–2521. [CrossRef]
25. Green, J.M.; Larrosa, C.; Burgess, N.D.; Balmford, A.; Johnston, A.; Mbilinyi, B.P.; Platts, P.J.; Coad, L. Deforestation in an African biodiversity hotspot: Extent, variation and the effectiveness of protected areas. *Boil. Conserv.* **2013**, *164*, 62–72. [CrossRef]
26. Hall, J.M.; Burgess, N.D.; Rantala, S.; Vihemäki, H.; Jambiya, G.; Gereau, R.E.; Makonda, F.; Njilima, F.; Sumbi, P.; Kizaji, A. Ecological and Social Outcomes of a New Protected Area in Tanzania. *Conserv. Boil.* **2014**, *28*, 1512–1521. [CrossRef]

27. Pfeifer, M.; Burgess, N.D.; Swetnam, R.D.; Platts, P.J.; Willcock, S.; Marchant, R. Protected Areas: Mixed Success in Conserving East Africa's Evergreen Forests. *PLoS ONE* **2012**, *7*, e39337. [CrossRef]
28. Giliba, R.A.; Mafuru, C.S.; Paul, M.; Kayombo, C.J.; Kashindye, A.M.; Chirenje, L.I.; Musamba, E.B. Human Activities Influencing Deforestation on Meru Catchment Forest Reserve, Tanzania. *J. Hum. Ecol.* **2011**, *33*, 17–20. [CrossRef]
29. Seiferling, I.S.; Proulx, R.; Peres-Neto, P.R.; Fahrig, L.; Messier, C. Measuring Protected-Area Isolation and Correlations of Isolation with Land-Use Intensity and Protection Status. *Conserv. Biol.* **2012**, *26*, 610–618. [CrossRef]
30. Behr, D.C.; Cunningham, E.M.; Kajembe, G.; Mbeyale, G.; Nsita, S.; Rosenbaum, K.L. *Benefit Sharing in Practice: Insights for REDD+ Initiatives*; Program on Forests (PROFOR): Washington, DC, USA, 2012.
31. Climate-Smart Agriculture Guideline for the United Republic of Tanzania: A Country–Driven Response to Climate Change, Food and Nutrition Insecurity. 2017. Available online: http://www.fao.org/3/a-i7157e.pdf (accessed on 4 December 2019).
32. Felix, M.; Gheewala, S.H. A Review of Biomass Energy Dependency in Tanzania. *Energy Procedia* **2011**, *9*, 338–343. [CrossRef]
33. Nzunda, E.F.; Midtgaard, F. Deforestation and loss of bushland and grassland primarily due to expansion of cultivation in mainland Tanzania (1995–2010). *J. Sustain. For.* **2019**, *38*, 509–525. [CrossRef]