Forest and woodland regeneration dynamics and persistence in the human-modified landscape of Greater Gombe Ecosystem, Tanzania

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Dedication

To my parents

Abstract

The clearing of tropical forests and woodlands for human use puts many species at risk of extinction. Vast areas of forests and woodlands have been converted to fragmented patches located within mosaics of different land uses (e.g., agricultural lands and human settlements). Some conservationists have argued that community-managed forests can be an effective strategy for promoting forest regeneration, persistence of mature forest patches, and conservation in human-modified landscapes. However, few studies have systematically evaluated its effectiveness. In particular, limited empirical evidence exists on the influence of these reserves on promoting the persistence and recovery of forest structure, carbon stock, and feeding habitat quality for vulnerable species, such as chimpanzees. To properly assess the influence of this management strategy, we need to take into account other factors likely to affect forest attributes, including, topographic factors (e.g., slope), anthropogenic factors (e.g., wildfire), and plant functional traits (e.g., dispersal mode) on the variation of forest structure in these reserves. To provide insights on these issues, I used various data sources to assess forest cover changes, factors affecting those changes and patterns of forest structure, composition, carbon stock, and feeding habitat quality for primates in 16 Village Land Forest Reserves (VLFRs) in the Greater Gombe Ecosystem (GGE), in western Tanzania. The data sources include, remote sensing confirmed with ground-truthing, forest inventory plots, spatially explicit forest monitoring data, and previously collected information on primate food tree preference. These VLFRs were established through a community-based planning process, facilitated by the Jane Goodall Institute and the Tanzanian government.

In this dissertation, I used three chapters to assess the effectiveness of community forest management at this site. In Chapter 1, I used multi-temporal satellite images from 2006, 2013, 2016, and 2021 to assess possible pathways of forest and woodland cover change in these reserves compared to unprotected village land. In Chapter 2, I quantify the relative influence of topographic and anthropogenic factors on the variation of forest cover change in these reserves. In Chapter 3, I determined how VLFRs promoted permanence and recovery of forest structure, carbon stock, and feeding habitat quality for primates and compared them with a nationally protected area, the Gombe National Park representing the reference scenario. Also in Chapter 3, I assess the relative influence of anthropogenic and topographic factors, as well as plant functional traits on the variation of forest structure in VLFRs. My results show that (1) between 2006 and 2021, forest cover increased by 66% in the area designated as VLFRs but declined by 22% in unprotected village land; (2) accounting for factors such as forest age, and topography, the factors that most impacted forest cover included a negative impact of fire frequency and a positive impact of village-led patrol effort; and (3) in comparison to the mature woodlands in the VLFRs, the second-growth woodlands in the VLFRs that have regenerated over the 15-years period since the intervention started exhibited basal area, carbon stock, and abundance of chimpanzee food plants at around 75%, 50%, and 77% respectively of the corresponding values observed in the mature woodlands within VLFRs. Furthermore, these forest attributes in the mature woodlands in the VLFRs exceeded 60% of the values found in Gombe mature woodlands. When accounting for factors such as forest age, dispersal mode, and topography, a factor that most impacted above-ground biomass and stem density included the positive influence of village-led patrols. The insights gained from this dissertation can provide valuable lessons for enhancing community forest management practices in similar tropical contexts, critical for increasing habitat quality for wildlife, improving landscape-scale connectivity, and contributing to climate change mitigation.

Table of Content

List of Tables

List of Figures

Introduction

Worldwide, humans are altering the environment on a massive scale and pushing many species to extinction and changing the climate. Vast areas of forest and woodlands in the tropics have been converted to fragmented patches located within mosaics of different land uses, including agricultural lands and human settlements (Elgar et al., 2014). Human modifications of these natural systems reduce the quality, quantity, and spatial connectivity of essential habitats for the maintenance of biodiversity and reduce the capacity of the natural systems to capture and store carbon critical for climate change mitigation. Strictly protected areas, such as national parks are useful tools for biodiversity conservation and carbon storage. However, these protected areas cover only 10% of the entire tropical forest biome (Gardner et al., 2009; FAO, 2020), precluding relying on them as a global solution to this problem. Furthermore, very few strictly protected areas are large enough to support viable populations of large and wide-ranging species (Plumptre et al., 2010). Therefore, conserving connected populations of such species requires finding solutions to conserve habitats on unprotected land (Mora and Sale, 2011). This will also assist in promoting carbon capture and storage. Concerted efforts by local communities, governments, and non-governmental organizations can promote conservation by identifying areas for community-managed forest that are critical for improving landscape-scale connectivity (Edwards et al., 2019). Such efforts can result in forest regrowth and persistence in these community-managed forests; however, multiple topographic (e.g., slope) and anthropogenic (e.g., fire) factors can influence regeneration and persistence. These issues raise questions that are the focus of this dissertation: *What are the factors that influence changes in forest structure, composition, and carbon stock in these community managed forests? How do these attributes of forest fragments influence communities of large vertebrates in human-modified landscapes?*

Ecological subdisciplines, such as landscape and community ecology, as well as the literature on secondary succession, inform the study of forest dynamics in human-modified landscapes. However, few studies simultaneously assess multiple factors to estimate the relative influence of anthropogenic and topographic factors on habitat regeneration and persistence. Many young forests and woodlands like many of these community managed forests are growing rapidly and thus absorbing carbon rapidly (Cook-Patton et al., 2020). However, there is limited knowledge regarding how fast carbon stock recovers in human-modified landscapes in Africa. Also, as wildlife such as primates are increasingly forced to inhabit human-modified landscapes, knowledge about how they can persist in regenerating landscapes is critical and is poorly understood (Rocha et al., 2018).

Landscape and community ecology studies have shown how different factors can influence biodiversity patterns in the landscape. Topographic attributes —such as elevation, slope, and aspect— can affect regeneration and persistence by influencing soil moisture availability, nutrients, and light availability (Chapman and McEwan, 2018). Topography can also affect regeneration and persistence by influencing human activities. For instance, areas that are steep and relatively high in elevation can promote the regeneration and persistence of woody plant communities simply because people cannot easily use these areas (Thomlinson et al., 1996). Anthropogenic factors, such as wildfire (Ryan and Williams, 2011), human population density (Dobert et al., 2014), dominant economic activities (e.g., fishing and agriculture), and forest patrols (Gonedele et al., 2019) affect forest regeneration and persistence in human-modified landscapes (Edwards et al., 2019). For some fire-resistant species, fire can break seed dormancy and promote regeneration (Neary and Leonard, 2015; Buramuge et al., 2023).

When fires are intense or frequent, fire can lead to arrested succession due to seedling mortality (Ryan and Williams 2011; Kelly et al., 2017). Areas closer to higher human population density are prone to anthropogenic impacts such as fire, and human development activities, such as charcoal production (Popradit et al., 2015; Crk, 2009). Communities involved more in fishing activities may influence reforestation and persistence more than communities involved in agriculture activities, as they do not need to clear so much land for crops. Moreover, forest patrols reduce human disturbances such as tree cutting for firewood and hence favor forest regeneration and persistence (Gonedele et al., 2019). However, these factors are rarely quantified among studies that have evaluated the effectiveness of the community managed forests in promoting forest regeneration, habitat quality for wildlife, and carbon stock recovery and persistence (Rasolofoson et al., 2015; Lupala et al., 2015). By empirically combining these factors, this dissertation provides valuable insight into understanding the important forces that control biodiversity patterns in human-modified landscapes.

Community conservation approaches such as Village Land Forest Reserves (VLFRs) give local people the right to own and manage their land (URT, 2007). While some conservationists advocated this approach (Agrawal and Gibson 1999; Ribot, 2003; Blomley 2013), others raise concerns. Some conservationists worry that communities may not be effective at managing the resources on which they rely for subsistence (Oates, 1995).

Therefore, critics argue that community involvement might result in weaker enforcement of conservation rules, leading to increased threats to biodiversity (Gibson and Marks, 1995; Wilshusen et al., 2002; Duguma et al., 2018). Despite skepticism and concerns, the community conservation approach is still popular among conservationists. It has been introduced into official policy and law in more than 20 African countries, including Tanzania (Barrow et al., 2016). Between 2000 and 2012, 509 VLFRs were declared by Tanzania village and district councils (URT 2012; Gross-Camp et al., 2019). For this dissertation, I focus on 16 VLFRs that are close to Gombe National Park in the Greater Gombe Ecosystem (GGE). The GGE, centered on Gombe National Park and its iconic chimpanzee population, is an example of a human-modified landscape, in which human activities have drastically degraded forest and woodland habitats outside the park. In an attempt to reverse these losses, the Jane Goodall Institute (JGI) and the Tanzanian government facilitated the establishment of VLFRs near Gombe through a community-based planning process that started in 2005. These VLFRs have since regenerated naturally. Currently, no study has been done to assess the influence of these reserves on forest structure, composition, feeding habitat quality for primates, and carbon stock change. This dissertation begins to address this gap in knowledge and sheds light on the debates about the forces that control species occurrence, distribution, abundance, richness, and carbon stock in human-modified landscapes.

Chapter 1:

Community-managed forests promote forest cover increase in the human-modified landscape of the Greater Gombe Ecosystem, Tanzania.

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Abstract

Deforestation can impair ecosystem functions, reduce biodiversity, and accelerate climate change. One strategy proposed to decrease deforestation and restore degraded areas involves community management of forests: entrusting local communities to manage forest reserves. However, the effectiveness of this strategy remains poorly understood. Here, we assess the impact of community management in the Village Land Forest Reserves (VLFRs) of the Greater Gombe Ecosystem (GGE), Tanzania, using Landsat satellite images from multiple dates (2006, 2013, 2016, and 2021) to assess the extent to which 16 VLFRs promoted forest regrowth and permanence. We detected a 66% forest cover increase in VLFRs but a 22% decrease in unprotected village land. Nonetheless, of land reforested between 2006 and 2013 in the VLFRs, 11% suffered re-clearing by 2021. Ensuring the persistence of these reserves requires additional measures.

Significance Statement

Community-based forest management has become widely adopted in Africa as an alternative to strictly protected areas, such as national parks, since the 1980s. However, comprehensive studies examining its effectiveness are lacking. To ensure its success, it is crucial to understand the outcomes of this approach. In this study, we evaluated how effectively village lands forest reserves enhance forest cover and permanence in the Greater Gombe Ecosystem in western Tanzania. In addition, we assessed the impact of a novel approach of village-led patrols on forest cover change. Compared to outside these reserves, forest cover has increased in these reserves. The findings from this study will contribute to enhancing forest management strategies in similar tropical contexts, leading to more effective forest conservation efforts.

Introduction

Human activities currently cause an alarming annual net loss of 4.7 million ha of forests and woodlands worldwide (FAO, 2020). Africa alone accounts for ~83% of this loss (FAO, 2020; FAO and UNEP, 2020). As forests and woodlands contain an estimated 75% or more of terrestrial biodiversity, this loss poses a major conservation threat. In addition to destroying habitats for diverse animal species, forest loss reduces the capacity of terrestrial areas to provide key ecosystem services for people and accelerates climate change (Manyanda et al., 2020). While strictly protected areas, such as national parks, help prevent forest loss, more than 80% of global forested areas are located outside such protected areas (Gardner et al., 2009; FAO, 2020). People living in rural communities rely heavily on forests for their livelihoods. With proper planning and management, these resources can be managed sustainably, and degraded areas can be reforested (Duguma et al., 2018). The recent finding that from 2010 to 2020, 625 million ha of forest in Africa—both inside and outside protected areas— regenerated naturally, demonstrates that it is possible to reverse the current forest loss trend (Mansourian and Berrahmouni, 2021). Addressing the ongoing decline in forest cover also aligns with global initiatives like the United Nations Convention on Biological Diversity Kunming-Montreal Global Biodiversity Framework. Target 2 of this framework aims to achieve effective restoration of at least 30% of degraded terrestrial areas by 2030. Similarly, Target 3 seeks to ensure effective conservation of at least 30% of terrestrial land, particularly in areas of significant biological importance, by the same deadline.

Given that strictly protected areas encompass less than 20% of global forest regions (FAO, 2020), relying solely on them is insufficient to fulfill objectives such as those outlined in targets 2 and 3 of the UN Convention on Biological Diversity Global Biodiversity Framework. This underscores the need to identify strategies for restoring and managing forested areas beyond these protected areas. Given the challenges and ethical considerations linked with expanding strict protection areas (Mora and Sale, 2011), community forest management emerges as a compelling alternative approach for advancing afforestation and ensuring the sustained presence of reforested areas (Nzali and Kaswamila, 2019; Wilson et al., 2020). This approach potentially benefits both woody plant communities and local livelihoods (Rasolofoson et al., 2015). Starting in the 1990s, governmental and non-governmental organizations in over 35 African nations have attempted to reverse the trend of forest and woodland loss by promoting the establishment of community-managed forests through participatory land-use programs (Hutton et al., 2005; Barrow et al., 2016; Duguma et al., 2018). These community-managed forests aim to restore degraded and deforested areas, conserve forests and woodlands, and support community livelihoods (Gumbo et al., 2018). Community forest management is popular among conservationists. Out of more than 35 countries in Africa that have attempted to establish community-managed forests, 20 have an enabling policy framework in place (Barrow et al., 2016). In Tanzania alone, by 2012, more than 2.3 million ha have been placed under different forms of community-based forest management through participatory land-use programs (URT, 2012; Nzali and Kaswamila, 2019). One such community-based forest management program is the Village Land Forest Reserve (VLFR) (URT, 2007). As of 2012, 509 VLFRs have been declared by the Tanzanian government and district councils (URT 2012; Gross-Camp et al., 2019).

While the community forest management approach has been widely adopted, the extent to which it succeeds in promoting reforestation and permanence of forests remains unclear. Recent studies in tropical regions have shown that people regularly clear second-growth forests, even as soon as 5 years after regeneration (Schwartz et al., 2017; Nunes et al., 2020; Schwartz et al., 2020). Therefore, even if community-managed forests successfully promote regeneration, the ability of second-growth forests to continue delivering ecological services, such as carbon sequestration and habitat for wildlife, will depend on whether this land-management system also promotes the permanence of forests and woodlands in the landscape.

To gain insights into the effectiveness of community-managed conservation strategies, we examined data from 16 VLFRs in the Greater Gombe Ecosystem (GGE) of the Kigoma

Region, Tanzania. Gombe National Park, the heart of this conservation area, has become a global icon of wildlife research and conservation, thanks to the first and longest-ongoing long-term field study of chimpanzees, begun by Jane Goodall in 1960 (Goodall 1986; Wilson et al., 2020). By the early 1990s, researchers at Gombe increasingly recognized that while habitat within the park has been well protected, activities such as clearing land for crops and cutting trees for firewood had resulted in the drastic degradation of forest and woodland habitats outside the park. In 1994, Goodall and colleagues organized a team of Tanzanian staff to go into the communities surrounding Gombe, listen to their needs, and develop a program to help. The Lake Tanganyika Catchment, Reforestation and Education (TACARE) project that resulted led to the community-led conservation approach that today drives the work of the Jane Goodall Institute (JGI) across the chimpanzee range in Africa.

As part of the TACARE process, JGI began in 2005 to facilitate conservation efforts in western Tanzania through the implementation of land-use plans in 27 villages (Wilson et al., 2020; Pintea and Bean, 2022). These land-use plans resulted in the establishment of approximately 45 VLFRs (Wilson et al., 2020), but in this study we focused on 16 of these which are those close to Gombe National Park. In each village, volunteers called "Village Forest Monitors "patrol the VLFRs. "Village Forest Monitors" are selected by their village governments to represent their own communities. JGI, through funds from the United States Agency for International Development (USAID) and other donors and technical partners support the volunteers with monthly field allowances compensating their travel and other costs, and also provide smartphones, mobile solar charging kit, and training to use Esri's Survey 123 apps to take the GPS location of patrolled areas, photographs of wildlife, and evidence of illegal human activities, and upload these data to a shared database in ArcGIS Online. Overall, this approach seems promising, but the extent to which it has succeeded remains to be determined.

To assess the effectiveness of this conservation strategy, we used multi-temporal satellite imagery, combined with ground-based surveys and extensive records of monitoring efforts. We categorized the landscape into three different management types: national park, VLFRs, and unprotected village land ("control"). We investigated the extent to which different land-cover transitions occurred over time in these three management types. While some studies have assessed conservation impact by using data from two-time points (Lupala et al., 2015; Rasolofoson et al., 2015; Lusambo et al., 2016), this can mask any changes that happen at shorter time scales and makes it difficult to assess the extent of forest permanence. Possible trajectories in forest cover over time include 1) forest persistence: 2) reforestation: 3) forest loss: 4) reforestation reversal (areas that initially supported regrowth but then experienced decline); 5) forest loss reversal; and 6) lack of forest recovery (areas that remain unforested) (Figure 1.1). Because of these varied possible trajectories, a comprehensive understanding of regeneration pathways requires multi-temporal data with a temporal resolution that matches the dynamic processes of early forest regeneration and clearance.

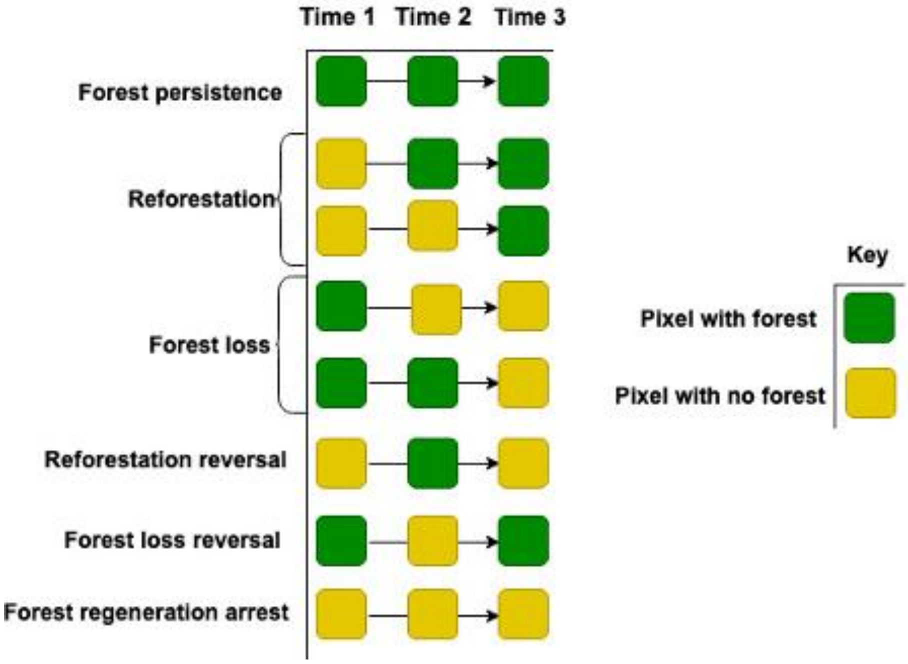

Figure 1.1: Potential trajectories of land-cover change.

To assess the realized pathways of land cover change in these reserves, we compared land-cover status in three years: 2006, 2013, and 2021. We focused on forest cover as our remotely sensed response variable of interest. VLFRs around Gombe primarily consist of woodlands, with very little evergreen forest. Therefore, we combined woodland and evergreen forest into a single forest category. We did the same for Gombe to maintain consistency even though it contains substantial evergreen forests. We used the 2006 image to provide a baseline satellite image for the year the GGE Project began. Although this project began in 2005, we could not find a cloud-free satellite image in 2005 for the same time of year as other images. The 2006 image nonetheless provides an appropriate baseline, because the land use planning process had just started, and the project had not yet designated any VLFRs (Pintea & Bean, 2022). We used a statistical matching method, using the difference in difference (DiD) regression model (Erbaugh, 2022), by matching the forest cover status of the intervention (VLFRs) and control (unprotected village land), both before and after the intervention, to understand the influence of the VLFRs in promoting forest cover increase in the GGE. This approach also can be referred as Before-After-Control-Impact (BACI) design (Mora & Sale, 2011). We sought to answer two questions. First, has forest cover increased in areas designated as VLFRs compared to unprotected village land? Second, do the VLFRs in the GGE promote forest cover permanence? We predicted that within Gombe, forest cover would remain unchanged. Compared to village adjacent lands, we predicted that within VLFRs, forest cover would both increase substantially and persist. We also predicted that monitoring efforts would be correlated with positive forest cover change within VLFRs.

Results

Land-cover classification accuracy

We classified seven images separately: four Landsat images —30m/pixel— (2006, 2013, 2016, and 2021), two pan-sharpened SPOT images—1.5m/pixel— (2016 and 2021), and one RapidEye image—5m/pixel— (2011). We used the higher resolution SPOT and RapidEye images to assist with Landsat classification. We focus on the Landsat data for our interpretation since these images provided greater temporal resolution. To classify the images, we used data from freely available historical high-resolution images in Google Earth Pro and ground surveys. We defined woodlands and evergreen forests as forest cover. Following the method proposed by Olosfsson et al., (2014) and FAO (2016) we computed the confusion matrix to evaluate the accuracy of the classified maps. The resulting median classification accuracy for these image sources was 89.11% for Landsat (range = 87.11% - 89.48% N= 4), 95.92% for SPOT (range = 95.02% - 95.92%, N=2), and 93.28% for RapidEye (N=1) (See SI Tables 1.4-1.11 for details). Classification from Landsat images thus exceeded the threshold of 85% considered to be reliable (Anderson et al., 1979).

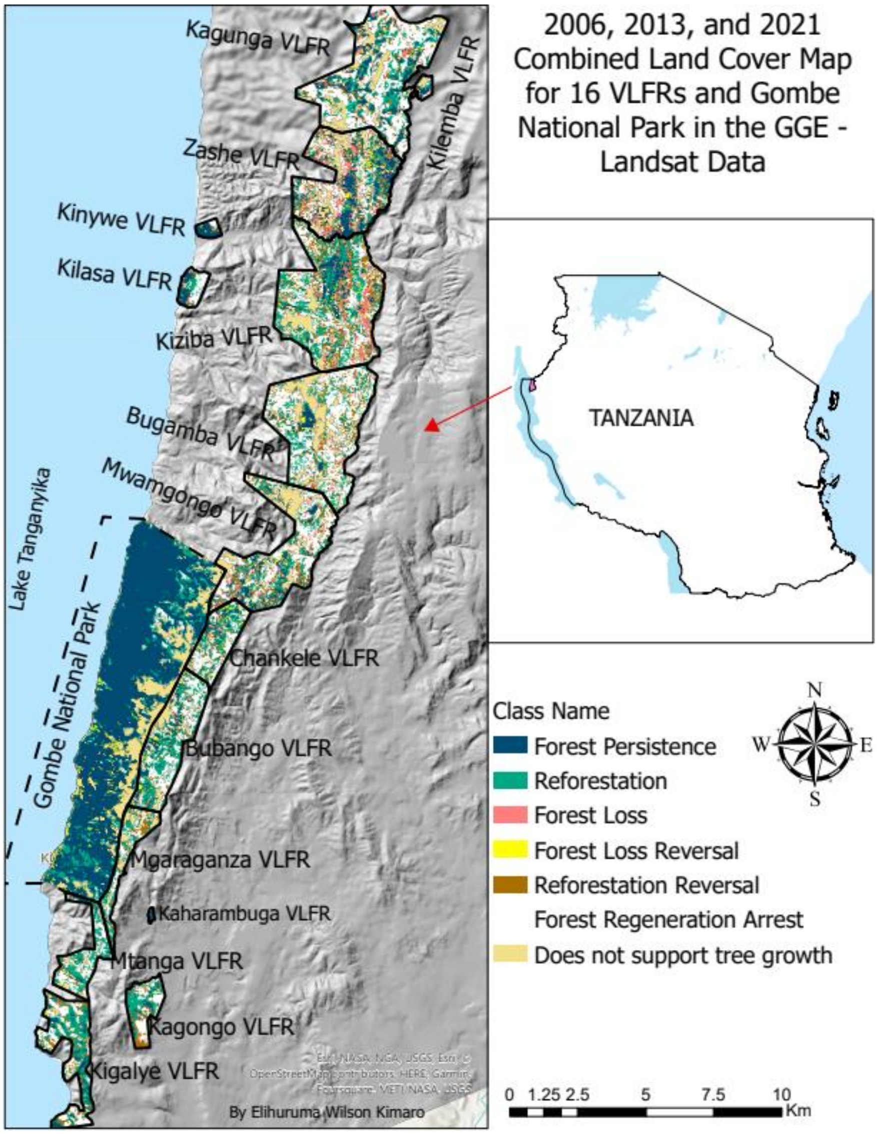

Figure 1.2: Map of Greater Gombe Ecosystem (GGE). Village Land Forest Reserves (VLFRs) are indicated in black solid lines.

Land-cover changes in the GGE

From 2006 to 2021, forest cover increased from 21.05 km^2 (~23% of the total areas that may support tree growth) to 34.87 km^2 (~40% of the total area that may support tree growth) in the VLFRs but decreased from 14.78 km^2 (~30% of the total areas that may support tree growth) to 10.59 km^2 (~19% of the total areas that may support tree growth) on unprotected village land. The DiD regression model supported the statistical significance of this forest-cover increase in the VLFRs compared to unprotected village land: assigning an area as a VLFR was associated with a 24.3% forest-cover gain compared to unprotected village land (β

= 0.243, SE = 0.0761, P<0.001). Furthermore, during this time, forest cover increased from 26.66 km^2 to 28.39 km^2 within Gombe National Park. The increase in forest cover in the VLFRs reached its peak in 2013 (37.16 km^2) and has changed little since then (Figure 1.3). Trees within the VLFRs continued to grow, however, with tree heights and diameter increasing. Out of 16 VLFRs, 15 experienced an increase in forest cover (median = 98%; range = 3-940, N=15), while one experienced a 15% reduction (Figure 1.4). To identify areas unlikely to support tree growth, such as rocky surfaces we used 1984 Landsat data by identifying bare/non-forest class. Our results show that 9.27 km^2 (9.95%) of the VLFRs is bare ground, while the remaining 89.89 km^2 (90.05%) is likely to support tree growth. As of 2021, ~50% of the VLFR area that could support tree growth remained unforested.

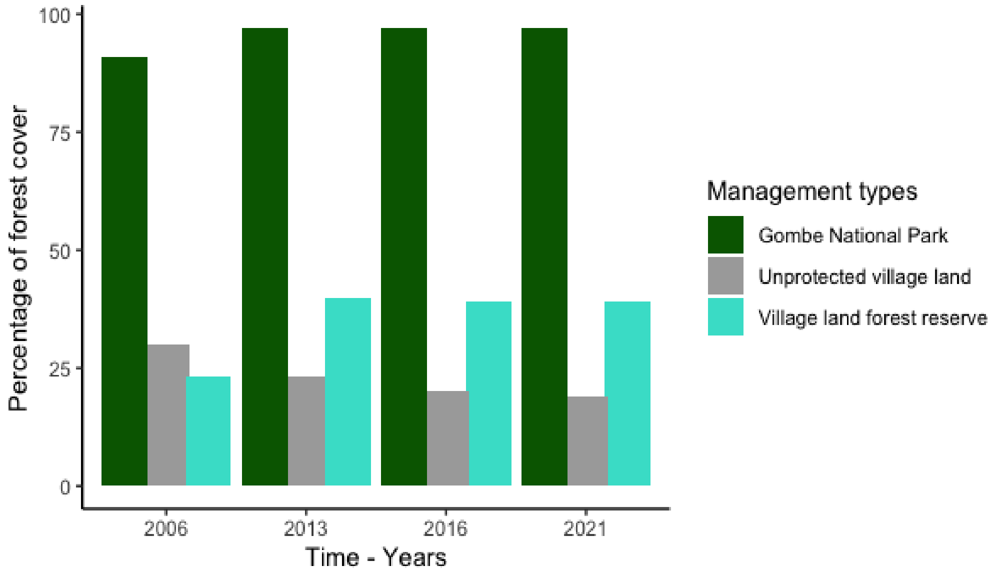

Figure 1.3: Percent forest cover increase from 2006 to 2021 in three different management types in the GGE. Gombe National Park, VLFRs, and unprotected village land. Percentages are calculated relative to land likely to support forest growth.

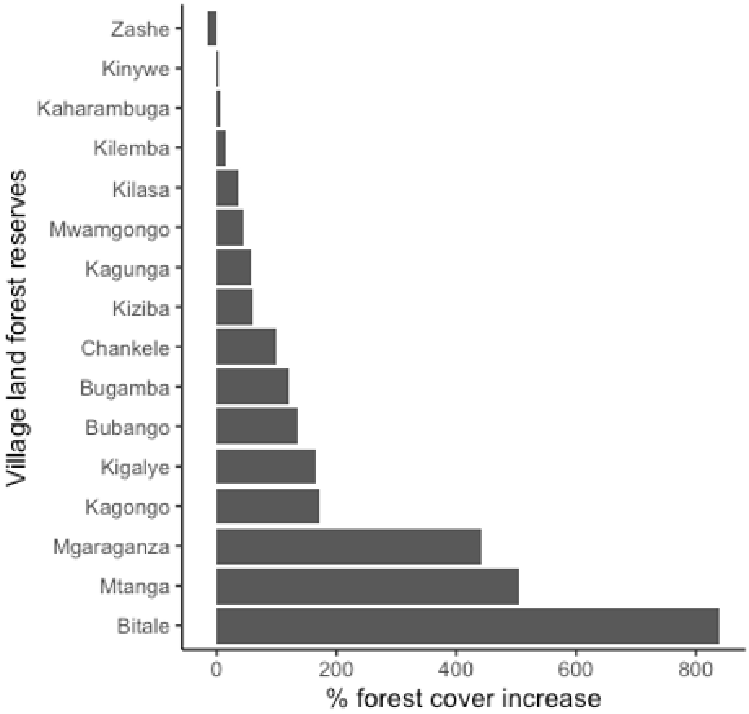

Figure 1.4: Percentage increase in forest cover for each of the 16 VLFRs in the GGE from 2006 to 2021.

Disaggregating forest cover measured in 2021 into categories of land-cover transitions (Figure 1.1) reveals more complicated dynamics. In Gombe and VLFRs, respectively, almost 95% and 57% of the forest cover that existed in 2006 persisted across the 2006-2013-2021 assessment interval. However, only 36% of the forest cover that existed in 2006 in the unprotected village land persisted through the same assessment interval. About 3% of forests cleared between 2006 to 2013 in the VLFRs regenerated between 2013 to 2021. However, in VLFR about 11% of forest regrowth between 2006 and 2013 underwent clearing between 2013 to 2021 (Figure 1.5). During 2006 and 2021 unprotected land experienced higher percentage of forest loss (22%).

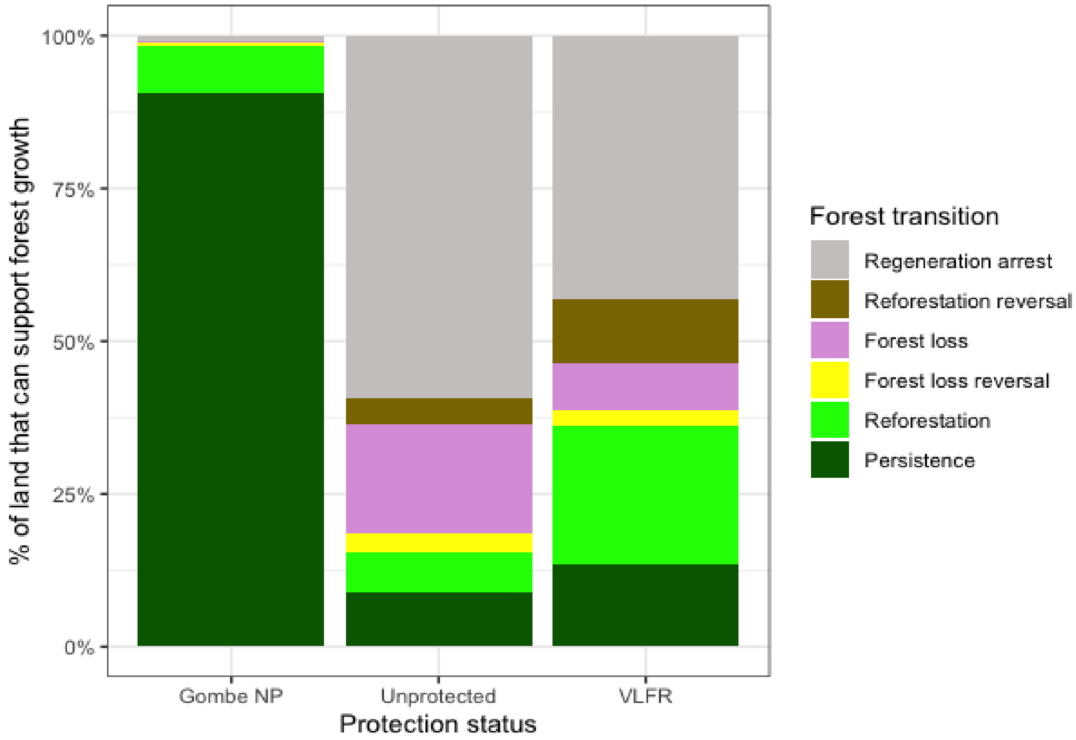

Figure 1.5: Aggregated land-cover trajectories over the study period over the three land-management types.

The role of monitoring in VLFRs

Multiple linear regression analysis demonstrated that of the three candidate models we examined—models with only 1 predictor, monitoring or proportion of initial forest cover (2006) and a model with a combination of these two predictors—the one with combination of monitoring and proportion of initial forest cover (2006) best predicted increases in forest cover and persistence. The extent of forest monitoring effort (m walked per ha) positively predicted both the growth of forest cover (β=0.08, 95% CI: [-0.01, 0.17]) and the persistence of forest cover (β=0.04, 95% CI: [0.02, 0.06]), although, the estimate for the influence of forest monitoring on the growth of forest cover included zero in 95% CI. We also observed small gains in forest cover in reserves that began with a higher proportion of forest cover in 2006 (Figure 1.6D). It is possible that community value more highly, and thus patrol more often, areas that already had high amounts of forest cover at the start of the program. We used the likelihood ratio test for nested models to rule out the possibility that initial forest cover reflected historical conservation practices of the community to an extent that obscures the significance of patrols. We used the proportion of VLFR in forest at the start of the program as an indicator of the historical forest use patterns in areas currently designated as VLFRs. The results showed that forest monitoring predicted forest-cover increase and persistence controlling for the presence of initial forest beyond that accounted for by initial forest proportion (p<0.0001, Chi square = 11.88, df=1). We also observed that smaller reserves received more monitoring effort than larger reserves (Figures 1.6F & 1.6G).

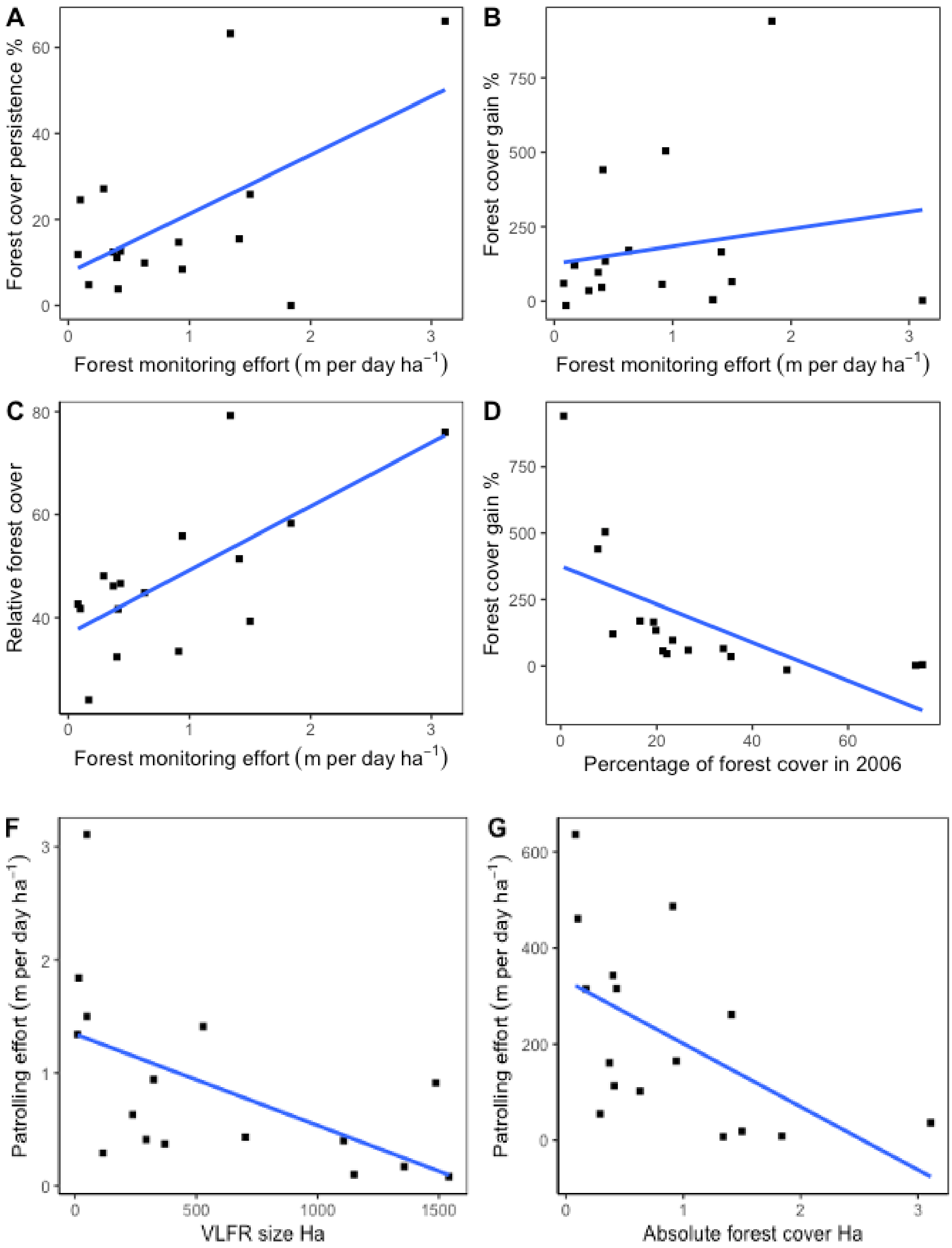

Figure 1.6: The role of monitoring in forest cover changes and its relation to forest cover and VLFRs sizes. A) forest monitoring in the VLFRs positively correlated with forest cover persistence (β =0.04, 95% CI: [0.02, 0.06]). **B**) Forest monitoring in the VLFRs correlated positively with forest cover increase, but the 95% CI of the parameter estimate included zero (β =0.08, 95% CI: [-0.01, 0.17]). **C**) Forest monitoring positively correlated with relative forest cover in the VLFRs (β= 0.04; P<0.001). **D**) Percentage of initial forest cover negatively correlated with forest cover gain (β = -0.01, 95% CI: [-0.01, 0). **F**) and **G**) VLFRs size and absolute forest cover negatively correlated with forest monitoring effort (β= -0.001, P<0.05 and β = -0.002; P<0.05 respectively).

Discussion

Even with the best of intentions, conservation policies can result in undesirable outcomes (Min-Venditti et al., 2017; Pintea & Bean, 2022). Because community forest management is a relatively new concept compared to centralized, government-led models such as national parks, the effectiveness of these policies needs to be evaluated (Duguma et al., 2018). This is also critical because it offer unique opportunity for understanding possible ways that can be used to promote restoration and effective management of forests outside strictly protected areas. The current global conservation initiatives, including the UN Convention on Biological Diversity Kunming-Montreal Global Biodiversity Framework stressed the needs to include areas outside strictly protected areas for forest management and restoration. These areas outside strictly protected areas are broadly termed as "Other Effective Area-Based Conservation Measures" by the Kunming-Montreal Global Biodiversity Framework (CBD, 2022). In this context, community-managed forests emerge as a promising framework for potentially harnessing Other Effective Area-Based Conservation Measures to facilitate forest management beyond strictly protected areas, thereby contributing positively to the overarching goals of the Kunming-Montreal Global Biodiversity Framework.

In our study, evidence from multi-temporal satellite image analysis supports the view that when implemented as part of community-led approaches such as The Lake Tanganyika Catchment, Reforestation and Education, VLFRs can increase forest cover persistence and regeneration. Between 2006 and 2021, the amount of forest cover in VLFRs increased by 66%, compared to a 22% decline in unprotected areas. Moreover, the DiD regression model revealed that VLFRs were associated with a 24.3% greater positive change in forest cover than unprotected village lands. Within the strictly protected Gombe National Park, forest cover also increased, but only by 7%, which is not surprising, given that the park contains extensive areas of natural grasslands and likely has limited space for forest expansion.

Despite this considerable success in both restoring and maintaining forests in the VLFRs, we note that the increase in forest cover peaked in 2013, covering only 50% of the areas that had tree cover in 1984. The newly formed forests are also proved susceptible to re-clearing by human activities, such as farming. Of forests that regenerated between 2006 and 2013 in the VLFRs, people subsequently re-cleared nearly 11% between 2013 and 2021. Also, we found that between 2006 and 2021, people cleared nearly 8% of the mature forest within areas nominally protected as VLFRs. Ensuring the full restoration and permanence of forest cover in this region requires additional measures. As local communities continue to rely substantially on forest resources for their means of subsistence, the risk of re-clearing remains a concern (Duguma et al., 2018). Unless additional measures are implemented, second-growth forests face risk being re-cleared, as has occurred at other sites (Heinimann et al., 2007; Gutierrez-Velez and DeFries 2013; Schwartz et al., 2017).

A key innovation of the VLFRs in this region involves the participation of VFMs selected by their own village governments. Previous studies have found that active monitoring of a reserve provides a strong deterrent to human threats, such as the cutting of trees for firewood and timber (Gonedele et al., 2019). Although many factors influence the dynamics of forest cover in the GGE, some of which may be cross-correlated and challenging to separate, we found strong links between patrol efforts and land-cover dynamics. Importantly, monitoring effort has a positive effect on forest gain and persistence including when we account for the effect of the proportion of forest cover present in 2006. However, the 95% confidence interval for the positive effect of patrol effort on forest gain included zero. This may be because, out of the 16 VLFRs, Kaharambuga and Kinywe VLFRs (Figure 1.1) started with more initial forest cover and therefore had little scope for increasing forest cover, but nonetheless experienced considerable patrol effort.

Because the monitoring of VLFRs depends on volunteers, we suspect that patrol effort reflects the extent to which people in different villages value their forests. Other factors that are likely to affect monitoring efforts include the proximity of VLFR to population centers, VLFR size, and relative and absolute size of initial forest patches. Monitoring effort correlated negatively with reserve size, suggesting that smaller areas are easier to patrol. A confounding factor is that of the five smallest reserves (Bitale, Kaharambuga, Kilasa, Kilemba, and Kinywe; Figure 1), all but Kilemba are situated close to population centers and are thus easy to patrol. Measures to encourage increased patrolling of larger reserves further from centers should aid reforestation and persistence. Additional potential measures include incentivizing villagers to patrol larger areas far from village centers, increasing monthly stipends, and providing training.

Overall, our study revealed evidence of success for community-managed conservation in the Greater Gombe Ecosystem. Nonetheless, challenges remain. Reforestation reversal and forest loss due to human development activities remain high risks because the challenge of balancing between development and conservation may continue for a long time to come (Duguma et al., 2018). Under the community forest management approach, communities are champions of managing the resources on which they mostly rely for their subsistence

(Fleischman et al, 2020). Thus, continuous efforts to empower communities to manage their own areas are crucial because, no matter what global aspirations or international commitments are made, reforestation and persistence will occur at the local level, in the community land (Pintea & Bean, 2022). Importantly, supporting the community-managed approach assessed here involved substantial inputs from USAID and other partners to cover costs and provide equipment and expertise for village land use planning, mapping, operationalization of land use plans, and allowances for VFMs. Replicating this process at other sites may require a similar scale of inputs to ensure success—which may be challenging for many locations. Finally, we hope the insights we provided here can contribute to a positive land-use plan review process currently being implemented in these villages in the GGE by JGI facilitation. We also hope that the insights gained here can provide valuable lessons for enhancing community forest management practices in similar tropical contexts.

Methods

Site Description

The GGE, located in northwestern Tanzania, covers an area of about 640 km^2 approximately the size of Singapore. It includes Gombe National Park (NP) and the land of 27 nearby villages with approximately 45 VLFRs (Wilson et al., 2020). Gombe NP forms the core area of the ecosystem, providing a habitat for wild animals, including an iconic population of chimpanzees, the subjects of the first long-term study of wild chimpanzees (Goodall, 1986). The recognition both that Gombe NP is too small to ensure the future viability of the chimpanzee population, and that the lives of people living around Gombe need to be improved, played a major role in prompting efforts to work with local communities to conserve forest and woodland and watershed outside of the park, leading to the establishment of VLFRs in these villages (Pintea, 2007).

Prior to the establishment of these reserves, much of this area was deforested by people engaged in subsistence farming, harvesting trees for building materials, and firewood. JGI and local government authorities in Tanzania have facilitated the establishment of these reserves through participatory land-use planning part of the larger approach of The Lake Tanganyika Catchment, Reforestation and Education, JGI's community-led conservation model. In this study, we focused on 16 of these VLFRs, which are those closest to Gombe (Figure 1.2). These 16 reserves cover 93.37 km^2 of the GGE and are located between 29.61166549^{0}E

4.83300698^0S in the south and 29.7234358^0E 4.4611497^0S in the north. These VLFRs contain complex topography characterized by mountains, escarpments, and their associated valleys. Elevation in the VLFRs ranged from 770 to 1800 m.a.s.l. Currently, JGI facilitates and builds capacity of the local communities to implement their land use plans and manage these reserves. This includes supporting the development of local community-based organizations and by training villagers to monitor their own forests. Village governments select one or more residents of each village who then volunteer to patrols the VLFRs and collect and report to the village and district governments their observations on wildlife and illegal human activities. JGI is providing the training and access to the necessary equipment, such as smartphones, mobile solar charging kit, Survey 123 app, ArcGIS Online and other mobile and cloud technologies to record their observations including pictures of illegal activities and any other information while monitoring the reserves. Village forest monitors used Garmin GPS units 2004-2009 (but project for establishing VLFRs didn't start until 2005), Open Data Kit (ODK) 2009-2019, and Survey 123 mobile app (2019-present) to record habitat health while patrolling the VLFRs. The data collected by the forest monitors include monitoring effort locations (recorded for approximately every 30 minutes from the start to the end of each patrol), animal sightings, and evidence of poaching and other illegal activities.

Remote sensing of forest change in the VLFRs

To quantify land-cover change we used cloud-free Landsat scenes, freely available from the USGS website. We performed image classification separately for each year using a Random Forest classifier. Because the Landsat scenes have a medium resolution (30 m/pixel), we used a smaller set of high-resolution satellite images (Olofsson et al., 2014): pan-sharpened QuickBird (0.6m/pixel), pan-sharpened SPOT (1.5 m/pixel), and RapidEye (5m/pixel) (Table 1.1) to assist with the Landsat image classification process. We did not rely on high resolution for our primary analysis because the high-resolution satellites are relatively new and thus limited in how far records extend back in time.

Remote sensing data

We sought to acquire Landsat imagery at roughly 5-year intervals from 2005 to 2020 for the study area. We focused on images from the early dry season (June – July) to minimize the chances of fire occurrences, which would distort our findings (misclassification of landcover). However, cloud-free images are notoriously difficult to obtain in tropical regions (Zhu et al., 2021). We acquired Landsat imagery for four years: 2006, 2013, 2016, and 2021.

We used the 2006 image (Table 1.1) as a baseline image. We purchased a RapidEye image from 2011 and two SPOT images from 2016 and 2021 (Table 1.1). To prepare each image for further analysis, we performed image registration, topographic correction, atmospheric correction, and radiometric calibration (Appendix I, SI).

To select training samples and perform an accuracy assessment, we used three different datasets: (1) processed QuickBird satellite imagery (0.6 cm/pixel) from July 2005 (acquired from the JGI archived remote sensing datasets (Pintea, unpublished data.); (2) ground-truthing surveys (Chapter 3); and (3) freely available historical high-resolution imagery in Google Earth Pro. For the ground surveys, we visited and recorded the location of different land-cover types in the GGE in 2021. In these surveys, we recorded 157 forest inventory plots and 150 random locations of different land cover types (woodlands, evergreen forests, oil palm farms, grasslands and bare land) (Chapter 3).

Table 1.1: Characteristics of the images used.

Imagery	Acquisition Date	Spatial Resolution (m)	Source
Landsat 5	3 July 2006	30	USGS
Landsat 8	22 July 2013	30	USGS
Landsat 8	14 July 2016	30	USGS
Landsat 8	28 July 2021	30	USGS
SPOT 7	07 July 2021	1.5	APOLLO
SPOT 6	26 July 2016	1.5	APOLLO
RapidEye	10 July 2011	5	APOLLO

Image classification

For each image, we overlaid the GGE boundaries to extract areas of interest, specifically, the VLFRs and comparison sites. The comparison sites included (1) unprotected village land and (2) protected land within Gombe NP. To identify unprotected village land in the GGE, we first masked out all areas that received some form of protection such as woodlots (areas reserved for fire-wood collection), private forests, forest reserves, and Gombe. We obtained polygons for these areas from the JGI office. We also removed all other areas under monitoring which were out of the polygons obtained from the JGI office. We identified those areas under monitoring by mapping the GPS coordinates uploaded by forest monitors since 2012. We then hand-digitized the remaining area for each village by including forested areas and avoiding developed areas in 2006. The last control polygons were distributed across the landscape, focusing on villages with VLFRs.

We performed supervised image classification separately for each image using a Random Forest classifier. We used 70% of the training data for the classification process and 30% for accuracy assessment (see SI Table 1.1 for details, Appendix I) (Olofsson et al., 2014). We classified each image using the following land-cover categories: evergreen forest—a dense and moist forest with no grasses on the ground, woodland—vegetation dominated by trees with an open canopy and grasses on the ground, oil palm, and unclassified lands (i.e., farms, bare ground, and other forms of land cover). We calculated forest cover as the total area of both evergreen forest and woodland in the classified images. To reduce spectral confusion in land cover classification due to the complex topographic terrain of the GGE, we employed a stratified strategy, performing image classification separately for each village. Following the method proposed by Olosfsson et al., (2014) and FAO (2016) we computed the error matrix to evaluate the accuracy of the classified maps.

Producing final maps

We produced final maps for the calculation of forest cover dynamics by removing areas that may not support tree growth, such as rocky surfaces. To exclude these surfaces, we used cloud-free surface reflectance Landsat imagery taken in 1984 (See SI Table 1.2 for details. Appendix I) to prepare a raster layer of two classes: areas with tree cover as a potential area for tree growth and areas with no tree cover as a non-potential area for tree growth. Landsat scenes before 1984 are available for the study area, but they are of coarser resolution (60 m per pixel) than those used in the land-cover classification (30 m per pixel). Therefore, to match the pixel values of images we used in the land-cover classification between 2006 and 2021, we selected the image from 1984, which is the first year that 30 m resolution scenes started to appear in our study area. In doing so, we erred towards generating a conservative estimate of the potential area for tree growth, but that might have ensured that we have masked out all the non-potential areas for tree growth.

To prepare this raster layer (defined here as the mask layer) we first normalize the 1984 Landsat bands to the respective bands in 2013, using relative radiometric method (SI, Appendix I). Then we calculated the Normalized Difference Vegetation Index (NDVI) to assess areas with live green vegetation. To further characterize the NDVI values and obtain areas with tree cover and non-tree cover, such as barren and grasslands we used two types of data: a) ground surveys dataset, and b) locations with no tree cover based on the visual interpretation of false-color composite (Near-Infrared, Red, Green) of the Landsat scenes.

Village forest monitoring dataset

In the VLFRs, patrols by village forest monitors may lessen unlawful activities like farming and logging, thereby fostering the regrowth and permanence of woody plant communities. We used data gathered by the VFMs, who used Open Data Kit (ODK) mobile app since 2012 and Survey 123 mobile app since 2019 to record patrol locations, animal sightings, and illegal activities, to quantify forest patrol efforts. We obtained the patrol locations for each VLFR using the VLFR polygons and then used the R (4.1.0) package "geosphere" (*v 1.5-18*) to determine the patrol distance (in meters) each day per hectare for each year. We then computed the mean distance patrolled each day per hectare for each VLFR over the course of 10 years (2012 to 2021). For 38 out of 160 VLFR-years (10 years per VLFR), we lacked sufficient data for inclusion in the study, due to the challenges of using mobile technologies in remote rural environments such as access to power to charge smartphones, and other hardware and software issues. In the final data set patrolling effort ranged from 0.08 to 3.11m per day ha^{-1} with a median value of 0.53 m per day ha^{-1}.

Statistical analysis

We used the difference in difference model (DiD) approach to assess the impact of establishing VLFRs on land-cover change in the GGE. The DiD is a non-experimental statistical method used to assess intervention effects by comparing intervention and control groups, across pre-intervention and post-intervention periods (Fredriksson and Oliveira, 2019). This approach can also be referred as Before-After-Control-Impact design approach (Mora and Sale, 2011). In the context of the current study the treatment refers to VLFRs and the outcome of interest is a forest cover increase. Thus, we investigated if areas designated as VLFRs have significant forest cover increases compared to unprotected village land. Also, even though there are many factors that influence the dynamics of forest cover in the GGE, some of which are correlated and challenging to separate, we can still inquire about the impact of patrols on land-cover dynamics. These factors include the proximity of VLFR to population centers, VLFR size, and the relative and absolute size of prior forest patches. To determine the effect of patrols and the proportion of forest cover in 2006 (initial forest cover) on the likelihood of the persistence of mature forest patches and transition to the forest, we used an information-theoretic model selection approach (Burnham and Anderson, 2002), employing a set of multiple linear regression models, each intended to represent a hypothesis explaining the response variable. We conducted all regression analyses for the persistence of mature forest and transition to forest separately. We ranked the models using the Akaike Information Criterion corrected for small samples (AICc) (Akaike, 1974). We used model selection to calculate model-weighted parameters to understand the likely effect of each parameter in the models (Burnham et al., 2011).

It is possible that community value and thus patrol areas that already had high amounts of forest cover at the start of the program. To assess if forest patrols have positive influence after accounting for proportion of initial forest cover which signal historical forest use patterns in the VLFRs we performed the likelihood ratio test for nested models (Lewis et al., 2011).

Candidate model set.

We specified a small number (N=3) of candidate models, given the limitation of small sample size (N=16 VLFR), we specified 3 candidate models for forest cover persistence and reforestation separately to assess the influence of forest patrols in the VLFRs:

1. *Forest patrol model:* patrolling efforts would be correlated with positive forest cover change.
2. *Initial forest cover model:* Areas with a high proportion of area in forest at the start of the VLFR program experience less reforestation than those with a low proportion.
3. *Global model (forest patrol +initial proportion of forest cover):* Forest cover persistence and reforestation vary with patrol effort and initial forest cover.

To test the influence of forest patrols above the proportion of initial forest cover using the likelihood ratio test for nested models we specified two candidate models:

1. *Initial forest cover model:* Initial forest cover indicate historical land use patterns in VLFRs, and because these patterns are so strongly maintained, they obscure the significance of patrols.
2. *Combined model (Initial proportion of forest cover + patrols):* After accounting for initial forest cover patrols explain significant variation of positive forest cover change in the VLFRs.

Chapter 2:

The relative influence of topographic and anthropogenic factors in forest cover change in the human modified landscape of the Greater Gombe Ecosystem, Tanzania

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Abstract

Effective conservation of forests requires tools in addition to strictly protected areas, such as national parks. One potentially effective tool for forest conservation involves community-managed forests. Assessing the effectiveness of such strategies can prove challenging because multiple factors affect regeneration and forest persistence, including topographic (e.g., slope) and anthropogenic (e.g., fire) factors. Thus, restoring biodiversity in human-modified landscapes requires an understanding of factors that influence regeneration and persistence. Here we assessed the relative importance of topographic and anthropogenic factors by comparing changes in forest cover at the pixel level between 2006 and 2021in community-managed forests in the Greater Gombe Ecosystem (GGE) in western Tanzania. We characterized the changes in forest cover into the following categories: mature forest cover persistence; second-growth forest regeneration; lack of forest recovery; and forest loss. Then, we randomly selected 3,500 pixels and used an information-theoretic approach by employing multiple logistic regression to assess the relationship between forest-cover change and 13 topographic and anthropogenic variables as well as the spatial structure of the community-managed reserves, such as reserve size. While forest regeneration and persistence decreased with increasing fire frequency, and building density, the regeneration and persistence increased by reducing distance to Gombe and increasing forest patrols. This study demonstrates that fire, often linked to agricultural activities and charcoal production, constitutes a prevalent forest disturbance in the GGE. Notably, reserves subjected to more frequent patrols exhibited reduced incidence of fires, underscoring the necessity of improving patrols in these reserves to ensure sustainability.

Introduction

Worldwide, humans have cleared more than 2.5 billion hectares of forest and woodland since 1850 (Houghton, 1999). Currently, the rate of net forest loss remains exceptionally high, with ~ 4.7 million hectares of forest lost annually (FAO, 2020). Africa alone accounts for 83% of global net forest loss (FAO, 2020). Nonetheless, sites within Africa also provide hope for reversing the forest loss trend. Between 2010 and 2020, Africa has supported regeneration of about 625 million ha of forest and woodland through natural regeneration (Mansourian and Berrahmouni, 2021). Forest cover has also grown substantially in other parts of the world, particularly in Europe and North America (FAO, 2020; Goran Stahl et al., 2020). Critical areas for reversing forest loss lie outside national parks and other legally protected areas. In Africa, ~75% of forest areas are outside strictly protected areas, and they are the most vulnerable to deforestation (FAO, 2020). Considering the practical and ethical challenges associated with expanding strictly protected areas, community forest management offers an intriguing alternative means to promoting forest regeneration and permanence in areas outside nationally protected areas (Duguma et al., 2018; Wilson et al., 2020).

The community forest management approach involves creating community-managed forests and giving people in villages rights to own, manage, and benefit from forests. (Brockington, 2007; Nzali and Kaswamila, 2019). (In the following, we use the term “forest” broadly to include any landscape dominated by trees, from closed forests to woodlands.) Since the 1990s, Tanzania and other 34 African nations, notably those in sub-Saharan Africa, have adopted this strategy by promoting participatory land-use programs (Barrow et al., 2016). The programs aim to restore degraded and deforested areas and promote the persistence and sustainable utilization of remnant forest patches (Gumbo et al., 2018). As of 2012, the Tanzanian government and district administrations had designated 509 community-owned forest reserves, officially known as Village Land Forest Reserves (VLFR) (URT 2012). The few studies that have assessed the effectiveness of the community forest management approach in Africa have found mixed results, with ranging from evidence of success in promoting forest cover increase (Lupala et al., 2015; Lusambo et al., 2016; Tripathi et al., 2020; Libois et al., 2021), to no effect (Rasolofoson et al., 2015), to unsuccessful (Mongo et al., 2013; Makunga and Misana et al., 2017; Singh et al., 2018; Hajalalaina et al., 2021; Ota et al., 2021).

Multiple factors influencing forest cover changes in human-modified landscapes likely contribute to these mixed findings, including both topographic attributes, such as slope, aspect, and elevation, and also anthropogenic factors, such as human population density, fire, forest management activities (e.g., forest patrols), and social-economic activities (e.g., fishing, agriculture). The relative influence of these factors on forest regeneration and forest cover persistence in community-managed forests remains poorly understood. Topographic attributes can affect regeneration processes directly by influencing soil moisture availability, nutrients, and light availability (Chapman and McEwan, 2018). Topography can also affect the regeneration and persistence of forests indirectly by influencing human activities. For instance, areas that are steep and relatively high in elevation can promote the regeneration and persistence of woody plant communities simply because people cannot easily use these areas (Thomlinson et al., 1996; Sandel and Svnning, 2013). Additionally, areas with higher human population density are more prone to anthropogenic impacts such as tree cutting for fuelwood gathering and timber (Crk, 2009; Popradit et al., 2015). While low intensity, infrequent fires can benefit some forests, by breaking seed dormancy for some tree species promoting regeneration (Neary and Leonard, 2015), fire can lead to arrested succession due to seedling mortality when high intensity or frequently recurrent (Ryan and Williams 2011), Also, the dominant social-economic activity (e.g., agriculture or fishing) can influence forest regeneration and the persistence of remnant forest patches. Because they do not have to clear as much land for crops, communities engaged in fishing, for example, are more likely to support the regeneration and permanence of remaining forest patches than communities engaged in agriculture.

Furthermore, spatial characteristics of the community-managed forest, such as reserve size and shape may modify the vulnerability of reserves to human impacts. Reserve shapes with a greater ratio of perimeter to surface area–such as long and narrow, rather than wide and circular shapes—result in more relative edge area, and thus greater vulnerability to human impacts (Haddad et al. 2015). Likewise, smaller reserves may not support as much forest regeneration and persistence compared to larger reserves, as they provide a smaller total area for the forest to regenerate and persist (Dobert et al., 2014). However, a larger reserve may also pose management challenges, such as limited capabilities of villages to regularly monitor the whole area due to higher patrolling cost. The forest patrols in these community reserves are critical because they have shown the capability of reducing human threats, such as cutting trees for timber and fuel (Gonedele et al., 2019).

To gain insight into how these factors simultaneously interact to influence community-managed forests in human-modified landscapes, we examined their relative influence on forest regeneration and persistence in 16 VLFRs which are those close to Gombe National Park in the Greater Gombe Ecosystem (GGE). Gombe NP is famous for the first long-running long-term study of wild chimpanzees, begun in 1960 by Jane Goodall (Pintea & Bean et al., 2022). Conserving the chimpanzees of Gombe NP has prompted many efforts to promote conservation in the region. The VLFRs in the GGE are the product of conservation efforts to incentivize forest regeneration and protection of the current and historic chimpanzee habitat outside Gombe NP. By the 1990s, human activities in this ecosystem had severely damaged the forest ecosystem outside the park (Pintea, 2007). To reverse these losses, the Jane Goodall Institute (JGI) established a community-centered conservation program in 1990s, the Lake Tanganyika Catchment Reforestation and Education project (Pintea & Bean et al., 2022). Through this initiative, starting in 2005, with funds from the United States Agency for International Development (USAID), JGI and Tanzanian government facilitated the establishment of VLFRs near Gombe through a community-based planning process (Wilson et al., 2020; Pintea & Bean et al., 2022). These VLFRs have since been allowed to regenerate naturally with no harvest allowed in the period under review. This is monitored by volunteer community members called “Village Forest Monitors” who use smartphones and mobile apps such as Survey 123 to record and share their observations of wildlife and illegal human activities in their VLFRs. Village governments select village forest monitors while JGI provides them with training, access to mobile smartphones and apps and field allowances to compensate their travel and other costs.

To assess the influence of multiple anthropogenic and topographic factors on forest cover change in these reserves, we first identified pixels with forest cover persistence, regeneration, loss, and arrested succession by combining land cover maps of the region—from Chapter 1— for the years 2006 and 2021. Then we randomly selected 3,500 pixels (covering a total of 315 ha) and used an information-theoretic approach to investigate the relative influence of VLFRs spatial characteristics, topographic, and anthropogenic variables on forest cover change. We predicted that higher fire frequency has negative influence on forest regeneration and persistence while higher forest patrols, slope, and wet areas have the positive influence.

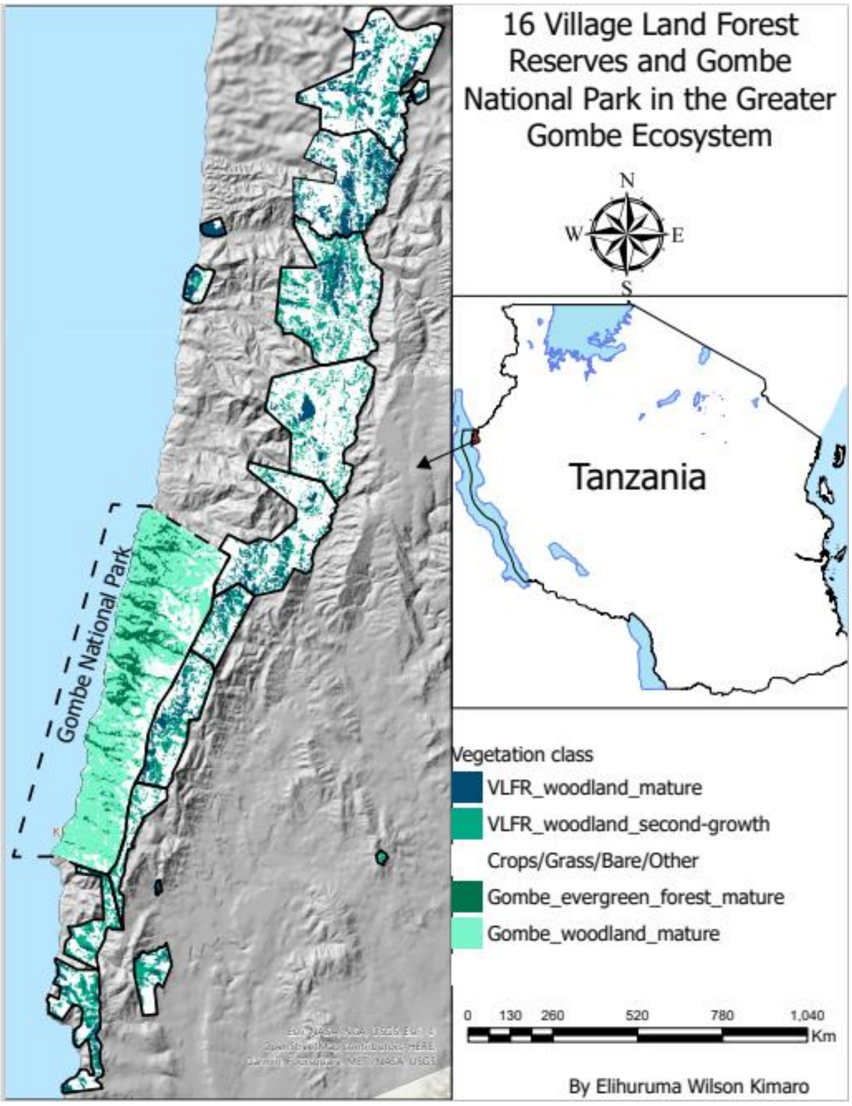

Figure 2.1: Vegetation classes in the 16 VLFRs and Gombe National Park in the GGE.

Material and methods

Study area

The GGE is a geographical area in northwestern Tanzania that includes Gombe NP and the land of 27 nearby villages (Goodall et al., 2022). The ecosystem covers about 64000 ha with approximately 45 VLFRs (Wilson et al., 2020). These reserves are the products of conservation efforts led by the JGI and Tanzania government to incentivize forest regeneration and persistence of forest cover outside Gombe NP. Prior to the establishment of these reserves, much of this area was deforested by people engaged in subsistence farming, harvesting trees for building materials, and firewood. In this study, we focused on 16 of these VLFRs, which are those closest to Gombe, Figure 2.1. These 16 VLFRs cover 9337 ha of the GGE and are located between 29^0 36’ 61” E and 4^0 49’72” S in the south and 29^0 43’E and 4^0 27’18’’S in the north. VLFRs in the GGE contain complex topographic patterns characterized by mountains ranging from 770 to 1800 m.a.s.l, escarpments, and their associated valleys.

The JGI currently supports building capacity of the village governments and community-based organizations to maintain and manage these reserves in the GGE. This includes supporting VFMs and equipping them with mobile devices and apps and monthly field allowances to compensate their travel and other costs. From 2005 to 2009, VFMs used Garmin GPS devices. From 2009 to 2012 they used Android smartphones and tablets and Open Data Kit (ODK). In 2019 VFMs switched from ODK to Esri’s Survey 123 that allowed users to visualize the data in-near real time using ArcGIS Online and Dashboards. The data collected by the forest monitors include patrol effort locations, animal sightings, and evidence of forest threats, such as cutting of trees. This unique dataset of forest monitoring effort provides an opportunity to use forest patrols (distance patrolled per day per ha) as among the predictors of forest cover change in the VLFRs of the GGE.

Land cover data

We used 2006 and 2021 land-cover maps of the study area (Chapter 1) based on Landsat data to identify four landcover types; 1) mature forest persistence as pixels that were classified as forest in 2006 and remained forested in 2021; 2) forest regeneration as pixels that were unforested in 2006 and forested in 2021; c) arrested succession patches as pixels that were unforested in 2006 and remain unforested in 2021—this includes crops and bare, built up, and fallow land; and d) forest loss patches as pixels that had a forest in 2006 but have no forest in 2021. To exclude surfaces that may not support tree growth, such as rocky surfaces, we used a mask layer prepared in Chapter 1 from cloud-free surface reflectance Landsat imagery taken in 1984, Table 2.1. The mask layer has characterized NDVI values showing areas with trees in 1984 as potential areas for tree growth and non-tree areas, such as barren and grasslands as areas that may not support tree growth.

Sample selection

We first removed areas that may not support tree growth in the land cover map using the mask layer. Then we randomly selected 3,500 pixels from all VLFRs that were scattered around the study area and are ≥100 m apart to reduce the effect of spatial autocorrelation

(Rasolofoson et al., 2015). To ensure similar sampling effort across reserve size, we selected 100 to 400 pixels (for reserves with an area < 300 ha) and 500 - 800 pixels (for reserves with an area >300 ha). We used land-cover change data for this sample of pixels to identify two response variables for regression analyses: the regeneration and persistence of forest cover.

Potential drivers

We consider a total of 13 potential drivers of forest cover change in VLFRs in the GGE (Table 2.2). Drivers included anthropogenic and topographic factors as well as spatial characteristics of the VLFRs.

1) **Anthropogenic factors**
   a) *Building density.* We employed building density as an indicator of the effect of human population density. Our assessment of building density primarily concentrated on individuals living within VLFRs. Although VLFRs legally prohibit. Our reasoning was that individuals living within VLFRs are more likely to contribute to deforestation and decrease regeneration compared to those living outside. To determine building density within VLFRs, we utilized point polygon building data extracted from 2005 Quickbird and 2017-2019 Maxar satellite images, using object based and Artificial Intelligence (AI) classification. Then LP converted the line polygons to point polygons. We sourced the building data from the JGI archived GIS and remote sensing datasets (Pintea, pers. comm.).
   b) *Fire.* Fire constitutes a predominant disturbance for woody ecosystems, influencing both vegetation structure (Bond and Keeley, 2005) and function (Kelly et al., 2017). fire regimes can also be used as a proxy for human activities, such as slash-and-burn farming and charcoal production (Chidumayo and Gumbo, 2013). We calculated the fire occurrence and extent using the Normalized Burn Ratio (NBR), which is an index designed to show burnt areas (Combee et al., 2021). We used the Landsat dataset to quantify the burnt areas annually and determined how often fires return to the same area over an 8-year period (2013 - 2020). We did not estimate the fire regime before 2013, because the Landsat program archive dataset for the relevant period (2006 - 2012) in the study area has less consistent temporal resolution. To guide the selection of the Landsat data, we used NASA fire archive point polygon incident data. The NASA fire data have a higher temporal resolution (daily observations) but poor spatial resolution, 200 m – 500 m per pixel. Each year, with the guidance of the NASA fire data, we

selected cloud-free Landsat scenes based on the following criteria: i) one pre-fire Landsat scene, and ii) multiple post-fire Landsat scenes. We then calculated the differenced NBR (*d*NBR) for each post-fire scene to a pre-fire scene and characterized the resulting *d*NBR to show burnt and unburnt areas using the scale proposed by Keeley (2009). We then summed the derived layer to generate annual dataset. Finally, we aggregated resulting yearly burned area layers into a final map of fire frequency showing how often fire return on each pixel for 8 years. Because we had reference data only for 2020, we performed an accuracy assessment only for the 2020 fire layer. We obtained reference data for 2020 from VFMs whom we requested to assist with this work while performing normal forest monitoring activities. We obtained 50 coordinates of burned area for 2020 and guided us for 50 coordinates of unburned areas. We then computed the error matrix to evaluate the accuracy of the 2020 fire layer. We used the method proposed by Olofsson and colleagues (2014) and FAO (2016).

c) *Forest monitoring.* Forest patrols may reduce illegal activities, such as farming and logging in the VLFRs, and hence promote the regeneration and persistence of woody vegetation. We used forest patrol effort—measured by distance walked per ha in these reserves from VFMs dataset generated in Chapter 1.

d) *Location of the VLFR in relation to dominant economic activity in the village.* The inhabitants of villages located near the lakeshore earn their living mainly through fishing, whereas inhabitants of inland villages depend more on agriculture (URT, 2019). As a result, lakeshore villages may promote forest recovery and persistence of remnant forest patches more than inland villages, as their inhabitants do not need to clear so much land for crops. In each pixel, we calculated the distance to the lake assuming that closer pixels to the lake are more associated with lake village characteristics than distant pixels.

e) *Distance to Gombe National Park boundary.* Proximity to Gombe may increase the likelihood of forest regeneration as Gombe may act as a seed source for adjacent lands. Likewise, it may influence regeneration and the persistence of forest cover due to increased support for conservation activities by the villagers, as most of the outreach programs from Gombe are concentrated in the villages bordering Gombe. The outreach activities that Gombe and other partners are implementing include conservation education, and support for social services, such as building classrooms and health centers. Residents of villages bordering Gombe may also benefit from permanent jobs, such as research assistants, which may incentivize people living closer to the park to support conservation activities.

f) *Number of villages surrounding a specific VLFR.* The number of villages bordering the VLFRs may influence mature forest persistence and regeneration success. Concerted efforts between villages to protect village reserves due to mutual benefits, such as catchment forests may positively promote forest persistence and regeneration. However, negative interactions, such as village boundary conflicts, may negatively affect forest cover persistence and regeneration.

g) *Village.* Village-level effects such as behavior of the villagers and differences in leadership may affect the probability of mature forest persistence and regeneration success. For this reason, we controlled for the village-level effect in all the proposed models. Out of 16 VLFRs, 4 of them share more than one village. Because we did not have a boundary assigned to each village for these 4 VLFRs, we combined the villages that share the VLFR into a single village, assuming they have combined effect on the shared VLFR.

2) **Topographic factors**

a) *Elevation, slope, aspect, and Terrain Wetness Index (TWI)*. Forest regeneration and persistence tend to occur at higher elevations and steeper slopes, where land is abandoned first, or humans cannot easily access those areas (Crk et al, 2009; Edwards et al., 2019). TWI is widely used to indicate soil moisture and therefore positively correlated with tree growth in the landscape (Mohamedou et al., 2019). To calculate slope, aspect, and TWI we used Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM).

3) **Spatial characteristics of the reserves**

a) *VLFR shape*. We used the following equation as proposed by Mcgarigal et al., (1995) to calculate the VLFR shape index: shape = $\frac{Perimeter}{2\sqrt{\pi * Area}}$

b) *VLFR area.* We used VLFR polygons to calculate area of the VLFR in ArcGIS Pro.

Table 2.1: Summary of the 13 drivers used in the logistic model.

Explanatory variables		**Data sources**
Anthropogenic factors	Building density	Point polygons data derived from QuickBird and Maxar Satellite Image of 2005 and 2017-2019 (Sourced from JGI – GIS office, Unpublished)
	Wildfire	Landsat Satellite Image (USGS)
	Forest monitoring effort	JGI – GIS office
	Distance to the Lake Tanganyika	-
	Distance to Gombe	-
	Number of villages surround a specific VLFR	
VLFRs spatial characteristics	VLFR shape index	-
	VLFR size	-
Topography	Elevation	Gombe database
	Slope	-
	Aspect	-
	Terrain Wetness Index	-
General effect	Village	-

Statistical analysis

We identified the following two response variables at pixel level; (i) forest cover persistence —coded here as 1 for persistence and 0 for no persistence (i.e., forest loss); and (ii) forest regeneration—coded here as 1 for regeneration and 0 for no regeneration (i.e., arrested succession)— between 2006 and 2021. Then we used an information-theoretic model selection approach (Burnham and Anderson, 2002 to determine the effects of topographic and anthropogenic factors as well as spatial characteristics of the VLFRs on the likelihood of the persistence of mature forest patches and transition to forest. We employ a set of multiple logistic regression models, each intended to represent a hypothesis explaining the response variable. We conducted all regression analyses for the persistence of mature forest and transition to forest separately. We examined the collinearity of predictor variables by calculating the variance inflation factor (VIF) (Naimi et al., 2014) and eliminated predictors with a VIF>3 (Cade, 2015; Carvalho et al., 2022).

We ranked the models using the Akaike Information Criterion corrected for small samples (AICc) (Akaike, 1974). We used model selection using *AICcmodavg* package in R (v 2.3-2) to calculate model-weighted parameters to understand the likely effect of each parameter in the models (Burnham et al., 2011). We interpreted explanatory variables whose model-averaged parameter estimate and 95% confidence intervals that exclude 0 as being significant.

Features of the environment tend to be spatially autocorrelated leading to a lack of independence in the model residuals (Gaspard et al., 2019). Although we obtained sample points randomly and at distances greater than 100 m, we tested model residuals for spatial autocorrelation using Moran's I test in the "sdpep" Package (*v 1.2-8*) in R (4.1.0). If we detected spatial autocorrelation in the residuals of each model with features of the environment data, we fitted another logistic model accounting for spatial autocorrelation (Dormann et al., 2007; Crk et al., 2009). We captured spatial configuration using spatial eigenvector mapping and included those eigenvectors that reduce spatial autocorrelation in the residuals into explanatory variables (Griffith and Chun, 2014).

Candidate model set.

We were interested in testing the influence of combinations of 3 main factors, 1) topographic factors, 2) anthropogenic factors, and 3) spatial characteristics of the VLFRs, on the likelihood of mature forest and woodland regeneration and persistence in the VLFR. Once again, forest persistence or regeneration were coded as binary response variables (i.e., 1 representing the focal land-cover change, 0 representing all other pixels) for each set of 3500 pixels for the two separate analyses. We specified 7 candidate models for forest cover persistence and forest regeneration separately to test our hypotheses. We also included a null model to quantify the support in favor of models relative to the null model. The following is a list of models we considered in this study:

1. *Null model:* forest cover regeneration and persistence are constant in the VLFRs.
2. *Topography model*: forest regeneration and persistence vary with topographic factors (Crk, 2009; Chapman and McEwan, 2018).
3. *Anthropogenic activities model:* forest cover persistence and regeneration vary with anthropogenic factors (Crk, 2009; Popradit et al., 2015).
4. *Topography + forest patrol model:* controlling for topography, forest patrol effort varies with regeneration and persistence of forest cover in the VLFRs (Khac et al., 2021).
5. *Topography + fire regime model:* Areas with relatively low rugged terrain and high moisture content favor human activities, such as clearing and burning for agriculture (Schmidt et al., 2016; Estes et al., 2017). As a result, regeneration, and the persistence of forest cover decreases.

6. *Fire regime + spatial characteristics model:* Larger and more complex VLFRs are more susceptible to human activities, such as clearing and burning for agriculture (Mengist et al., 2022). Consequently, regeneration and permanence of forest cover decreases.
7. *Global model (topographic + Anthropogenic + spatial characteristics):* Variations of the regeneration and persistence of forest cover follow a more complex pattern that cannot be explained by a few factors (Edwards et al., 2019).

Results

The number of pixels for the four landcover types were: 1) 1352 pixels (122 ha) for mature forest persistence; 2) 628 pixels (57 ha) for forest regeneration; 3) 965 pixels (87 ha) for arrested succession; 4) 555 pixels (50 ha) for forest loss. We considered all predictor variables as they had VIFs <2. The overall accuracy of estimating the burnt area for the year 2020, was 96.67%. We detected significant spatial structure (spatial autocorrelation) in the model residuals ($P<0.001$) for all models with topographic parameters. We therefore accounted for spatial autocorrelation before computing model-averaged estimates of each parameter in the model and selecting the models that best predict forest regeneration and persistence. The best model included topography and fire regimes and explains 96% of forest cover persistence and 99% of forest regeneration variation, Table 2.2 & 2.3.

Table 2.2: Summary of model selection: variation of forest persistence in the VLFRs

Factors	Topo+fire	Global	Topo	Topo+patrol	VLFR+fire	Human	Null	MAP	2.5%	97.5%
Yi	-1.17	4.71	0.91	2.5	5.58	4.17	0.89	-0.93	-3.79	1.92
Elevation	-0.004	0.004	-0.003	-0.004				0.00	0.00	0.00
Slope	0.02	0.05	0.02	0.02				0.02	0.01	0.03
Aspect	0.002	0.002	0.002	0.002				0.00	0.00	0.00
TWI	0.07	0.08	0.08	0.07				0.07	-0.01	0.15
Patrols		2.66		4.61		0.71		2.61	0.39	4.83
House density		-0.11				-0.005		-0.11	-0.2	-0.03
Fire	-0.17	-0.21			-0.18	-0.18		-0.17	-3.08	-0.06
Distance to Gombe		-0.022			-0.8	-0.074		-0.22	-0.36	-0.08
VLFRs shape		-0.56			-0.24	-1.2		-0.58	-1.62	0.45
VLFR area		-0.30				0.24		-0.3	-0.65	0.45
# of village		-0.29				0.05		0.29	-0.11	0.69
Distance to lake		0.0004				0.0004				
K	**34**	**36**	**33**	**34**	**16**	**18**	**1**			
Δ AICc	**0.00**	**12**	**10.7**	**12.6**	**204.5**	**207**	**304**			
w_i	**0.96**	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**			

Key: Topo=Topography; VLFR=VLFR spatial characteristics; TWI=Terrain Wetness Index.

Table 2.3: Summary of model selection: variation of forest regeneration in the VLFRs

Factors	Topo+fire	Topo	Topo+patrol	Global	Human	VLFR+fire	Null	MAP	2.5%	97.5%
Yi	-16.6	17.5	-20.6	0.73	-74	-88.7	0.89	-16.6	-646	615
Elevation	-0.001	-0.002	-0.002	-0.002				0.00	0.00	0.00
Slope	0.02	0.02	0.02	0.03				0.03	0.01	0.04
Aspect	0.004	0.003	0.004	0.004				0.00	0.00	0.00
TWI	0.03	0.04	0.04	0.009				0.03	-0.07	0.13
Patrols			20.8	-0.03	-12.4			20.8	-15	56.1
House density				-0.07	0.3			-0.07	-0.11	-0.03
Fire	-0.27			-0.28	-0.28	-0.292		-0.27	-0.38	-0.17
Distance to Gombe			-0.14	-0.23				-0.14	-0.19	-0.10
VLFRs shape				-0.09		45.4		-0.58	-1.62	0.45
VLFR area				-0.03		-29.7		-0.3	-0.65	0.45
# of village				-0.08	30.4			0.29	-0.11	0.69
Distance to lake				0.0004	0.0002			0.00	0.00	0.00
K	**43**	**41**	**42**	**32**	**19**	**17**	**1**			
Δ AICc	**0.00**	**31.6**	**32.3**	**52.2**	**255**	**270**	**397**			
w_i	**0.99**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**			

Key: Topo=Topography; VLFR=VLFR spatial characteristics; TWI=Terrain Wetness Index.

The model that included only anthropogenic factors had zero weight on the variation of forest cover and regeneration. However, anthropogenic factors, such as fire regime, forest patrols, and building supported predictions of the hypothesis. While fire and building density has a negative impact, patrolling in VLFRs promotes both forest regeneration and persistence. The patrolling effect estimates, however, included zero in a 95% confidence interval for forest regeneration (Table 3). According to NASA fire data, the 16 VLFRs in the GGE experienced 65 (median) fire incidences per year for 9 years, between 2012 and 2020. This was in the range of 52 to 115 fire incidences. However, the frequency of fires in these reserves has been declining since 2012. Regressing the frequency of fires with forest patrol efforts, we found a negative correlation (Figure 3b).

The proximity to Gombe NP has a positive impact on the maintenance and regrowth of forest cover in VLFRs, whereas we detected zero influence on proximity to the Lake Tanganyika. As predicted by anthropogenic hypothesis, steep slopes favored regeneration and forest cover persistence in VLFRs. We did not detect any influence of elevation or aspect on forest regeneration and persistence in our dataset. Nevertheless, moist area—predicted by higher terrain wetness index (TWI) values—favored both regeneration and persistence of forest cover in the VLFRs. However, the estimates of the effect of TWI included zero in 95% CI both for forest cover persistence and regeneration (Figure 2.2 & 2.3).

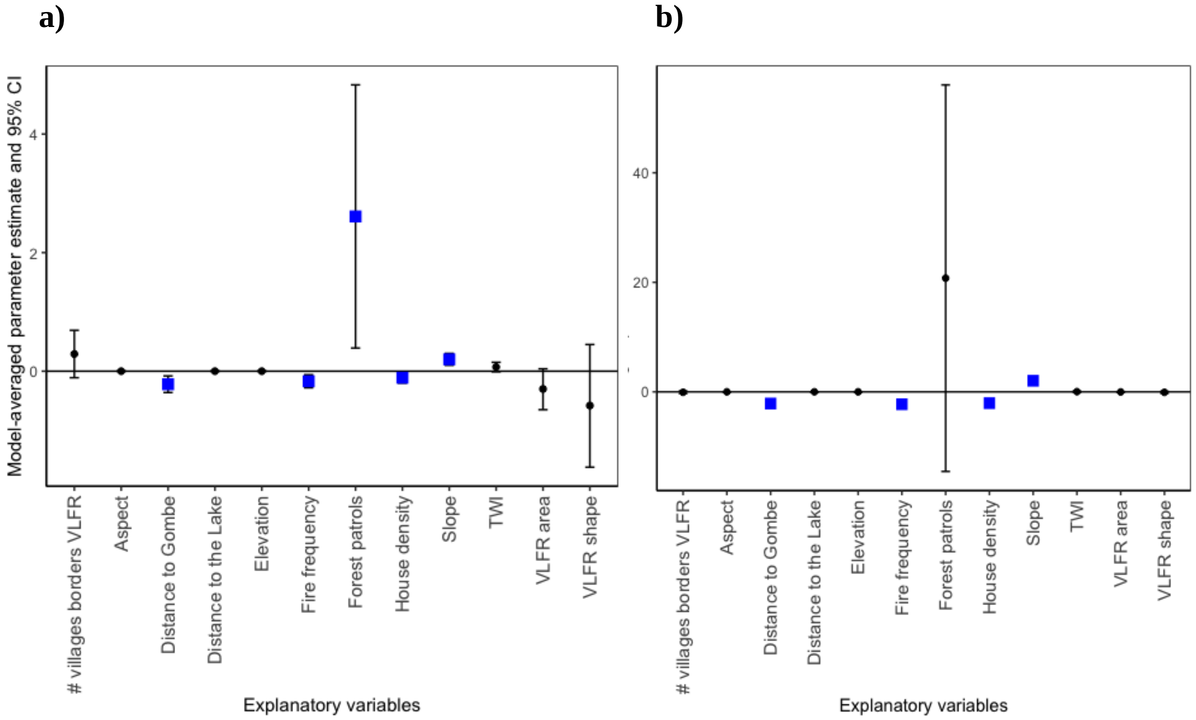

Figure 2.2: Changes in forest cover persistence and regeneration in VLFRs are largely explained by the same factors: distance to Gombe, fire frequency, and house density have negative influence while forest patrols and slope have positive influence**:** a) Forest cover persistence in which patrols by village forest monitors have larger effect than any other factor; b) Forest regeneration.

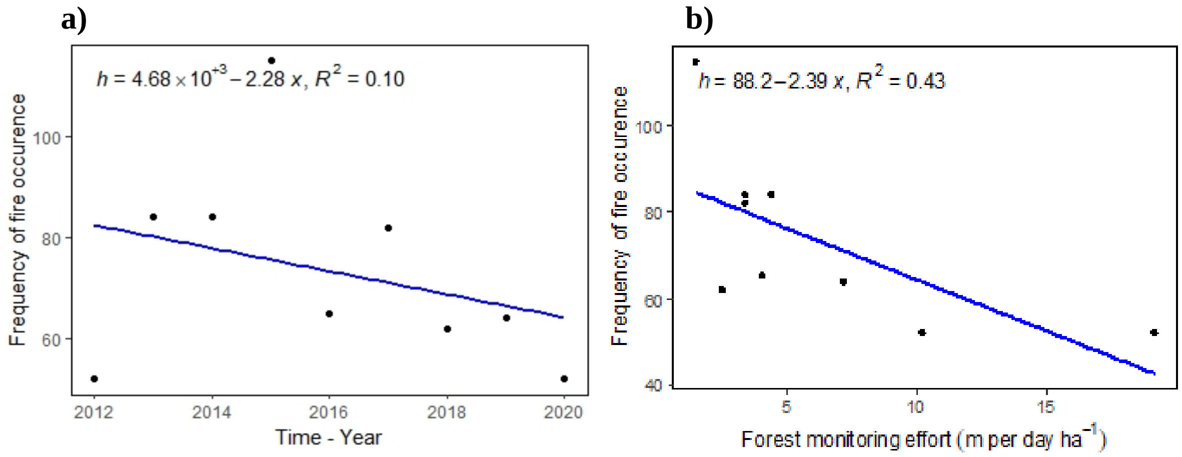

Figure 2.3: Fire occurrence in the GGE **a)** Annual fire incidences in the VLFRs for the years between 2012 and 2020 and **b)** Relationship between forest patrols and fire frequencies in the VLFRs

Discussion

Models that included topography and fire frequency largely predicted forest cover persistence (96% model weight) and recovery over a 15-year period (99% model weight) than other models we considered in this study. Of the various factors predicted to affect forest change, we found that proximity to Gombe, fire frequency, building density, forest patrols, and slope had the most impact. Some of these variables we examined here and their effects on forest recovery are similar to those from other studies: negative effect of fire frequency (Furley et al. 2008; Kelly et al., 2017), population density (Popradit et al., 2015) and positive effect of steep slope and proximity to strictly protected areas (Chazdon, 2003; Crk et al., 2009). A key innovation in the management of VLFRs in this region involves forest patrols by village forest monitors. As we predicted, forest patrols by village forest monitors positively influence forest cover change and negatively correlate with fire frequency.

Even though woodlands are considered a fire-tolerant ecosystem (Buramuge et al., 2023), frequent fires (e.g., repeated every year) do not provide enough time for seeds to germinate or for stumps to sprout and establish before the next fire event occurs. Recurrent fire also indicates human activities, such as swidden agriculture, and charcoal production (Chidumayo and Gumbo, 2013). Swidden agriculture involves creating fertile farm fields, clearing unwanted plants, and burning to regenerate soil nutrients (Styger et al., 2009). Forest cover declines as a result. The substantial number of annual fire occurrences—median of 65 (range =52-115) in these reserves suggests that people intentionally set many fires for land management purposes, such as agriculture and charcoal production. Fortunately, there is a downward trend in the number of fire incidents per year during the period from 2012 to 2020 (Figure 3a).

Forest patrols in these reserves may have contributed to the decreasing trend in fire incidents. Our findings showed a negative relationship between fire frequency and patrolling effort. Giving a positive indication of the role of forest patrols in reducing fire incidents in these reserves. Patrols also have a stronger effect on persistence than any other factor. One key feature of forest patrols by village forest monitors is that village government authorities receive reports from village forest monitors on human risks to forest resources in VLFRs. They— village forest monitors— also provide information about individuals involved in illegal activities. The decision to take legal action against those alleged individuals utilizing local bylaws is then up to the village government. The village forest monitors are therefore not members of the police or other law enforcement agencies, but rather conservationist volunteers. Even though this may be complicated, forest patrols by village forest monitors seem to promote forest cover persistence and regeneration in VLFRs. To ensure forest permanence in these reserves, it is critical to continue to invest in and improve forest patrols by village forest monitors.

As expected, the presence of people residing within VLFRs as estimated by building density has a detrimental impact on forest regeneration and persistence. A quick solution to the challenge of people living in these reserves will have a great positive impact on these reserves. As the number of people in these reserves grows, addressing this challenge in the future may be difficult. The influx of refugees from neighboring countries to Kigoma villages might contribute substantially to the population of individuals choosing to live in remote areas within these reserves (Pintea & Bean, 2022). Desperate for areas to seek shelter and cultivate for subsistence, refugees may opt for remote locations, including those within VLFRs in the GGE.

We found that proximity to Gombe NP positively influences forest regeneration and forest cover persistence. Perhaps the people living adjacent to Gombe support conservation more than those living away from Gombe in the GGE. The villages close to Gombe, such as Mtanga, Kigalye, Mgaraganza and Chankele, can be easily reached by conservation educators and conservation practitioners from different organizations including JGI and Tanzania National Parks (TANAPA). Therefore, higher outreach activities in villages adjacent to Gombe than in those far away might have helped promote a positive attitude toward conservation in villages close to Gombe. Further, residents of villages bordering Gombe benefit from permanent employment, such as research assistants working on long-term research activities conducted by JGI. People living closer to the park might have been motivated by these opportunities and supported conservation efforts. Gombe may also serve as a seed source for adjacent lands, thereby increasing regeneration.

Finally, as observed in other human-modified landscapes (Crk, 2009; Chapman and McEwan, 2018), steep slopes in VLFRs promote forest recovery and persistence. Slopes that are steep discourage human activities, such as agriculture, which may favor forest recovery and persistence (Jimenez et al., 2022). Additionally, while moist areas favor forest regeneration and persistence, they are also targets for human activities like agriculture. This may explain why the estimate for the effect of wetness on forest persistence and regeneration included zero in the 95% CI.

Conclusions

Compared to other factors, patrolling by village forest monitors had a large positive influence on forest cover persistence in VLFRs in the GGE between 2006 and 2021. Forest patrols also have shown a promising result in reducing fire frequency in these reserves. With the use of technology supported by the JGI, it is easier to track the extent of village forest monitors' efforts and the impact people in the GGE can have on the ground as a result. Therefore, continued efforts to promote patrols by village forest monitors coupled with data collection will enhance the management of these VLFRs, reducing forest threats, such as clearing the land for agriculture. As in many other parts of the tropics, fire is often associated with agriculture and charcoal production (Timberlake et al., 2010). Our observations were similar to those made in other tropical regions (Furley et al., 2008; Kelly et al., 2017) in which fire frequency negatively impacts forest recovery and persistence. Therefore, conservation organizations and people residing in the GGE should find ways to manage fire and related activities in these reserves. It is likely that many fire incidents in these VLFRs are caused by residents living within these reserves. These residents may engage in charcoal production and agriculture practices involving fire. Whenever feasible urgent efforts should be made to address the challenge of people living inside these reserves, as future efforts may become more challenging due to an expected increase in their numbers.

In addition to strengthening forest patrols, fostering positive attitudes towards conservation is essential for long-term sustainability. We have observed a positive influence of proximity to Gombe NP on forest cover changes in these reserves. This suggests that outreach activities and employment opportunities available to communities neighboring Gombe NP have contributed to their willingness to support conservation efforts. Alongside enhanced patrols, strategies to engage communities in ways that foster positive conservation support are vital. Outreach activities, such as conservation education and environmentally friendly income-generating initiatives like beekeeping, can stimulate local community support for conservation.

Chapter 3:

Community managed forests promote carbon sequestration, biodiversity, and quality habitat for primates in the human modified landscape of the Greater Gombe Ecosystem, Tanzania

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Abstract

Community forest management has been advocated as a tool to support forest conservation; however, few studies have systematically evaluated its effectiveness. We analyzed the impact of 16 Village Land Forest Reserves (VLFRs) in the Greater Gombe Ecosystem (GGE) in western Tanzania on the recovery and persistence of 7 forest attributes including forest structure, composition, carbon stock, and quality habitat for wildlife. We then compare these forest attributes for community-managed forests with those of Gombe National Park, representing the reference scenario. To further understand the effectiveness of VLFRs in the GGE we assessed the influence of other factors, including plant traits, topography, and human activities on forest structure. We found that second-growth woodlands in the VLFRs that regrew over the 15 years since the start of the intervention exhibited basal area, carbon stock, and abundance of chimpanzee food plants that were approximately 75%, 50%, and 77%, respectively, of the respective values for mature woodlands in the VLFRs. Also forest attributes for VLFR mature woodlands have over 60% of Gombe mature woodland values. This demonstrates VLFRs' ability to promote persistence of forest attributes in the GGE. When accounting for factors such as forest age, dispersal mode, and topography, forest patrols promote higher stem density, suggesting its influence in the recovery of forest in the GGE. We conclude that community-managed forests have the potential to promote the recovery and persistence of essential forest attributes, thereby enhancing quality habitat for wildlife, improving connectivity at the landscape scale, and contributing to climate change mitigation.

Introduction

Forests and woodlands play vital roles in maintaining healthy ecosystems (Huston, 1994). Forests-defined broadly to include a range of tree-dominated landscapes, from closed-canopy forests to woodlands—provide habitat for numerous organisms, and store ~45% of terrestrial organic carbon, which is critical for climate change mitigation (Jayakumar and Nair, 2015; Waring et al., 2020). Forests provide ecosystem services vital for human well-being: they protect watersheds, control floods, mitigate soil erosion, and contribute to clean air (Makunga and Misana, 2017). Although humans depend on many benefits from forests, human activities nonetheless cause an unprecedented rate of forest loss, with a net annual loss of 4.7 million ha globally (FAO, 2020). Africa alone accounts for 83% of this loss, as people increasingly clear land for agriculture (FAO, 2020).

The situation is not, however, hopeless. In landscapes modified for agriculture and other human-uses—which includes at least ~70% of terrestrial systems (Galan-Acedo et al., 2019)—forest fragments can persist and recover. Although some studies (278 studies) have shown that ecosystems undergoing recovery can attain ~27-33% of the attributes of the mature reference ecosystem in ~20 years (Moreno-Mateos et al., 2017), Poorter and colleagues (2021) found that across 77 sites in the tropics, secondary forests attained 78% (33 – 100%) of the attributes of mature forests through natural regeneration. This rate of forest recovery may vary across human-modified landscapes (Arroyo-Rodriguez et al., 2017), depending on factors including forest age (Powers et al., 2009; Yude et al., 2018), plant traits (e.g., dispersal mode) (Baker et al., 2009), and topographic and anthropogenic variables (Thong et al., 2020). As forests age, some forest attributes typically increase including basal area, tree height, biomass, carbon stocks (Powers et al., 2009; Poorter et al., 2016), and quality habitat for wildlife (Rocha et al., 2018) whereas the number of stems per unit area declines through thinning processes (Powers et al., 2009; Poorter et al., 2016). Topographic factors, such as slope, aspect, and elevation affect forest regeneration and persistence by influencing soil moisture availability, nutrients, and light availability (Powers et al., 2009; Chapman and McEwan, 2018). Plant traits, such as fruit size and dispersal mode, may influence tree distribution and seedling recruitment, due to plant-frugivore interactions (Fuzessy et al., 2016). The recruitment of seedlings, particularly of large-seeded species may be higher in areas with a larger population of large-bodied frugivore species, such as chimpanzees, due to the positive effect of their gut passage on seed germination and their capacity to disperse seeds long distances after eating fruits (Wrangham et al., 1994; Chapman and Onderdonk, 1998). The recovery of forest structure and function also tends to increase with the diversity of trees present/restored, due to negative density dependence and negative frequency dependence (e.g., Harms et al. 2000; Wills et al. 2006; Liang et al. 2016; Kalyuzhny et al. 2023).

In addition to these biotic factors, anthropogenic factors may influence forest regrowth and properties in human-modified landscapes in negative or positive ways. Areas closer to dense human populations experience more anthropogenic impacts such as fire and fuelwood gathering (Popradit et al., 2015; Crk, 2009). Socio-economic activities also play a role, as communities primarily involved in fishing may have more influence on forest regeneration and persistence than communities engaged in agriculture, which requires more land clearance for crops. Forest patrols can also have a major impact. Patrols, commonly implemented in strictly protected areas rely on law enforcement and substantial financial resources. Community-managed forests generally lack such resources, but even limited community-led patrols can reduce human disturbances such as tree cutting for firewood (Gonedele et al., 2019). However, the relative influence of these factors on forest structure variation in human-modified landscapes remains poorly understood. Understanding these dynamics is crucial for improving forest management policies and implementation, given that Africa continues to experience a higher annual deforestation rate than regeneration (FAO, 2020).

Despite the many challenges posed by deforestation, recent studies provide hope that the trend can be reversed. Although Africa accounts for a major proportion of global forest loss, forest recovery still occurs on a large scale in Africa. Between 2010 and 2020, ~625 million hectares of forest were recovered across Africa (Mansourian and Berrahmouni, 2021), demonstrating the potential for restoration and conservation of forests in African landscapes. This restoration not only provides more wildlife habitat but also contributes to carbon sequestration, a critical aspect of climate change mitigation. By focusing on restoration, Africa can also contribute to global conservation and restoration initiatives, including limiting the rise in average global temperatures to no more than 2°C above pre-industrial levels under the Paris agreement (IPCC, 2023) and restoring 350 million ha of degraded and deforested landscapes by 2030 under The Bonn Challenge (Uriarte and Chazdon, 2016; Dinerstein et al., 2019). Within The Bonn Challenge, Africa through the African Forest Landscape Restoration Initiative (AFR100) aims to restore 100 million ha. Focusing on restoration, Africa will also be able to contribute to the new UN Convention on Biological Diversity Global Biodiversity Framework, which aims to ensure, among other things, that at least 30% of terrestrial area is under effective conservation and at least 30% of degraded land is under effective restoration by 2030 (CBD, 2022). Promoting natural regeneration and forest protection in human-modified landscapes provides a critical opportunity to achieve these ambitious goals.

There are several strategies for promoting forest regeneration in human-modified landscapes. While traditional conservation approaches have primarily focused on establishing strictly protected areas like national parks, it has become evident that relying solely on these measures is insufficient to safeguard biodiversity and ecosystem services (Elleason et al., 2020). Strictly protected areas cover less than 20% of global forest areas (Berghofer, 2010; Elleason et al., 2020; FAO, 2020), whereas a much larger proportion of forest needs to be retained to ensure species survival and ecosystem functions (Tilman et al., 1993; Isbell et al., 2014). As a result, efforts to conserve and restore forests outside strictly protected areas are essential (Dinerstein et al., 2019). It can be possible to conserve forests in these areas by expanding strictly protected areas, but due to practical and ethical challenges, this strategy may not be feasible in human-dominated landscapes (Duguma et al., 2018). The community forest management approach may play a crucial role in this regard, as it offers an opportunity for communities to manage their own land and benefit from it (Blomley et al., 2008). However, the extent to which community forest management succeeds in promoting recovery and persistence of multiple forest attributes, such as forest structure, carbon stock, and quality habitat for vulnerable species remains poorly understood.

As a test case for community-managed forests, we focused on 16 Village Land Forest Reserves (VLFRs) in the Greater Gombe Ecosystem (GGE). The GGE is home to Gombe National Park and its renowned chimpanzee population (Pintea & Bean et al., 2022). By the 1980s, human activities in this ecosystem had severely damaged the forest and woodland ecosystems outside the park (Pintea, 2007). To reverse these losses, the Jane Goodall Institute (JGI) established a community-centered conservation program in the 1990s, the Lake Tanganyika Catchment Reforestation and Education project (TACARE) (Pintea & Bean et al., 2022). Through these initiatives, starting in 2005, with funds from the United States Agency for International Development (USAID), JGI and the Tanzanian government facilitated the establishment of VLFRs near Gombe through a community-based planning process (Wilson et al., 2020; Pintea & Bean et al., 2022). These VLFRs have since been allowed to regenerate naturally with no harvesting allowed in the period under review. However, the extent to which these reserves promote the recovery of forest structure, composition, carbon stock, and habitat quality for wildlife compared to their mature counterparts in the protected area of Gombe NP has not been systematically investigated. Furthermore, insofar as people are more inclined to protect plant species they view as useful, it is critical to understand forest characteristics perceived as important by local community members.

Equally as critical as understanding tree biodiversity and carbon dynamics in regrowing forests is understanding habitat provisioning at higher trophic levels. Primates, particularly chimpanzees, are of particular interest in our study area, because they are both vulnerable to forest loss and fragmentation (Barelli et al., 2015), and essential for forest persistence and expansion through seed dispersal (Chapman and Onderdonk, 1998). As an umbrella species, chimpanzees require large home ranges (Humle et al., 2016) to ensure a sufficient supply of their preferred food: ripe fruit (Wrangham et al., 1998). Saving chimpanzees may thus save many other species that share the same habitat (Simberloff, 1998). However, we do not know the extent to which successful restoration and protection of a network of forest and woodland fragments can provide quality habitat for chimpanzees in human-modified landscapes such as the GGE. Moreover, it is important to note that woodlands are more prevalent than evergreen forests within the VLFRs. Compared to evergreen forests, woodlands exhibit lower productivity (Lubala et al., 2014) and offer lower-quality feeding habitats for primates (Lindshield et al., 2021). Given these differences, it becomes essential to assess the potential of VLFR woodlands to provide long-term habitat quality for primates. In other words, because human disturbances (e.g., fire) often shape woodland ecology (Frost, 2009), when woodlands are protected from human disturbances for a long time, what is their capacity to provide primate habitat quality?

To address these knowledge gaps, we conducted an extensive study using various data sources, including forest inventory plots; information from long-term observations of chimpanzee food tree preferences; data on tree species preferred by local communities (Chepstow-Lusty et al., 2006); and spatial data on patrol efforts in VLFRs. Our study focused on seven key forest attributes as response variables: three attributes of forest structure (basal area, stem density, and above-ground biomass); forest tree species; above-ground carbon; chimpanzee feeding habitat quality; and abundance of trees perceived as important by people in the GGE. We used these forest attributes as indicators to assess the performance of VLFRs in promoting desired outcomes for forest conservation efforts in the GGE. Specifically, we assessed the recovery rate of forest attributes in VLFRs by comparing mature woodland and second-growth woodland that regrew in ~15 years. Furthermore, we investigated the extent to which VLFRs promote persistence of forest attributes by examining mature woodland in VLFRs and that of Gombe NP, representing the most favorable scenario. Additionally, we presented a general picture of what woodland in VLFRs could provide chimpanzees with tree food if protected in the long term. We did this by comparing long protected woodland and mature evergreen forest in Gombe NP, the habitat we know supports chimpanzees with food. While accounting for this relevant information, we explored a critical question: what is the relative influence of factors, including topography, tree functional traits, and anthropogenic factors on biomass and stem density in VLFRs? By investigating these aspects, our study aimed to 1) shed light on VLFRs' capacity to promote forest recovery and persistence in the GGE, and 2) provide insights on other important forces that control biodiversity patterns in the VLFRs, including topography, tree functional traits, and anthropogenic factors. This knowledge is critical for effective forest management and conservation strategies in the GGE and similar tropical contexts.

Thus, in this study we address four specific research questions (Table 3.1): (1) *How do forest attributes differ between mature (likely over 60 years) and second-growth (~15 years) woodlands in the VLFRs?* (2) *how do forest attributes differ between Gombe and VLFR mature woodlands?* (3) *how do forest attributes differ between mature woodland and mature evergreen forest in Gombe?* (4) *what is the relative influence of modifying variables—plant traits, age, topographic, and anthropogenic factors—on biomass and stem density variation in VLFRs?* We predicted that compared to second-growth woodland, mature woodland in the VLFRs would have higher basal area, biomass, carbon stock, and tree feeding habitat quality for primates. Moreover, we predicted that older VLFR woodland would be most similar to Gombe woodland in the values of these forest attributes. Also, because people selectively plant, or allow them to grow, trees they find useful or valuable for other cultural reasons, we expected that VLFRs would have a higher proportion of trees preferred by people than other tree species. We also predicted that compared to mature evergreen forests in Gombe NP, plots of mature woodland inside Gombe NP would have lower basal area, biomass, carbon stock, and tree feeding habitat quality for primates. Last, because forest patrols may reduce illegal human activities in these reserves, we predicted that among the different VLFRs, those with higher forest patrol efforts would promote the persistence and recovery of forest composition, carbon stock and chimpanzee feeding habitat quality than those with lower patrol efforts in VLFRs.

Table 3.1: A summary of research questions, statistical approaches, and number of different plots involved in each comparison.

Research questions	Statistical Analysis	Vegetation classes compared	# of plots
1). How do response variables differ between mature and second-growth woodlands in the VLFRs?	Linear mixed models	VLFR mature woodland VLFR second-growth woodland	102 75
2). How do response variables differ between Gombe and VLFR mature woodland?	T-test	VLFR mature woodland Gombe mature woodland	102 45
3). How do response variables differ between mature woodland and mature evergreen forest in Gombe NP?	T-test	Gombe mature woodland Gombe mature evergreen forest	45 35
4). What is the relative influence of modifying variables—plant traits, age, topographic, and anthropogenic factors—on biomass and stem density variation in VLFRs?	Multiple linear regression models	VLFR mature woodland VLFR second-growth woodland	102 75

2.0 Material and methods

2.1.1 Study area

We conducted this study in the GGE, an area in northwestern Tanzania that includes Gombe NP and the land of 27 nearby villages. The ecosystem covers ~64000 ha with approximately 45 VLFRs (Wilson et al., 2020; Goodall et al., 2022). Gombe NP forms the core area of the ecosystem and is the site of an iconic study of chimpanzees, the first long-term field study of chimpanzees (Goodall, 1986; Goodall et al., 2022). Many conservation initiatives in this area have been inspired by the desire to protect the Gombe chimpanzees. The realization that conserving the park on its own is insufficient to ensure the future viability of the study population prompted efforts to work with local communities to preserve forests, woodlands, and watersheds outside the park. A Greater Gombe Ecosystem Conservation Action Planning process using Conservation Standards identified conversion of forests to agriculture as the main threats. Major sources of these threats were lack of land use plans and lack of land tenure (Pintea, 2007). This led to the development of village land use plans and establishment of VLFRs in these villages by the local communities facilitated by local government authorities and JGI (Pintea, 2007; Pintea & Bean, 2022). Prior to the establishment of these reserves, much of this area was deforested by people engaged in subsistence farming, harvesting trees for building materials, and firewood. In this study, we focused on 16 of these VLFRs, which are those closest to Gombe (Figure 1). These 16 reserves cover 9337 ha of the GGE and are located between 29^{0} 36’ 61” E and 4^{0} 49’72” S in the south and 29^{0} 43’E and 4^{0} 27’18’’S in the north. These VLFRs have complex topography including mountains, escarpments, and steep valleys. Mountain peaks range from 770 to 1800 m.a.s.l.

The JGI currently supports building capacity of the village governments and community-based organizations to maintain and manage these reserves in the GGE. This includes supporting VFMs and equipping them with mobile devices and apps to record habitat health while patrolling. JGI also support village forest monitors with monthly field allowances to compensate for travel and other costs. From 2005 to 2009, village forest monitors used Garmin GPS devices before converting to Android smartphones and tablets and Open Data Kit (ODK) app. In 2019 VFMs switched from ODK to Esri’s Survey 123 that allowed them to visualize the data in-near real time using ArcGIS Online and Dashboards. The data collected by the forest monitors include patrol effort locations, animal sightings, and evidence of forest threats, such as cutting of trees. The vegetation in this ecosystem varies from evergreen forest in valley bottoms to woodland and grassland on higher slopes. Most of the evergreen forest is concentrated in Gombe NP along the streams. The VLFRs are dominated by woodland vegetation. Some VLFRs contain small patches of evergreen forest, but because they constitute only a small portion of tree cover, here we focus on woodlands. Therefore, not all vegetation classes were present in both the National Park and the VLFR because the park contained only mature forest, and the mature evergreen forests in the VLFRs were not included in the vegetation plot survey. Forest in Gombe NP is over 50 years old due to Gombe being protected since 1945 as a Game Reserve and subsequently gazetted as a national park in 1968 (Goodall et al., 2022). In the VLFR, mature woodlands are also likely over 50 years old, given that aerial photos show extensive tree cover in the region in 1972 (Pintea, 2007). We refer to these vegetation classes known or inferred to be older than 50 years as Gombe mature evergreen forests, Gombe mature woodlands, and VLFR mature woodlands. We refer to woodland in the VLFRs that has regenerated since 2006 as second-growth woodland.

2.1.2 Forest inventories and carbon stock estimates.

We established a set of plots to quantify forest structure, composition, and chimpanzee habitat quality, stratifying the sampling by land-cover type (i.e., evergreen, woodland) and management status (i.e., National Park or VLFR). We used a previously generated maps (Chapter 1) to identify four land cover types based on age (VLFRs mature woodland versus second-growth woodland—), management status (VLFRs versus Gombe mature woodlands), and forest types (Gombe mature evergreen forest versus Gombe mature woodlands).

Following previous studies in the tropics, we allocated the sampling effort of at least 0.2% of the total area of each vegetation class (Jayakumar and Nair, 2013; Muboko et al., 2013). In each vegetation class in the VLFRs, we randomly selected locations for 20 x 20 m square vegetation plots. In the southwest corner of each plot, we placed nested subplots measuring 5 x 5 m and 1 x 1 m, used for sampling saplings and seedlings, respectively. For Gombe NP, we re-surveyed existing vegetation plots of the same size (20 x 20 m), which were established by MLW in 2008. We counted and identified all trees >5cm DBH (diameter at breast [1.3m] height), (referred here as "adults") in each plot. In each 5 x 5 m subplot, we counted and identified all trees 1-5 cm DBH (referred to here as saplings) and counted and identified all trees <1 m height in each 1 x 1 m subplot (referred to here as tree seedlings). For each corner of the 20 x 20 plot, we identified the closest adult tree as the "corner tree." We measured the height of the 4 corner trees in each plot using a clinometer (Haglöf Electronic Clinometer) (Feldpausch et al., 2012). We used an elevation raster data layer with spatial resolution of 10 m from Gombe database developed by Pintea (2007). We then recorded the elevation, slope, aspect, and distance to nearest stream from the center of each plot.

To determine above-ground tree biomass, we used an allometric equation developed from a wide range of forest and woodland ecosystems in Tanzania (Mugasha et al., 2013): biomass = $\beta_0 DBH^{\beta_1} ht^{\beta_2}$, where ht is the tree height and β_0, β_1, and β_2 are the equation constants. Because we did not measure height for all recorded tree species, we used the trees with height measurement to construct a site-specific height-diameter model, using a Weibull equation (Feldpausch et al., 2012): Tree height = $1.3 + \beta_1(1 - e^{-\beta_2 D^{\beta_3}})$, where β_1, β_2, and β_3 are the regression coefficients, and D = DBH. We used the height-diameter model to estimate height for trees with DBH measurements but no measurements of height. We then calculated the tree above-ground biomass using allometric model separately for each vegetation class. We converted the biomass estimates to carbon, assuming that tree above-ground carbon (in Mg C ha^{-1}) is 45.6% of tree above-ground biomass (Martin et al., 2018; Cuni-Sanchez et al., 2021). In this analysis, we utilized bootstrapping with a resampling size of 1000 for each vegetation class to construct a 95% confidence interval for the mean carbon estimate. This approach allowed us to assess the uncertainty and variability of the carbon estimates and obtain a reliable range within which the true mean carbon value lies with 95% confidence for each vegetation class (Feldpausch et al., 2012). To calculate the total carbon stored in each vegetation class in the region, we used the forest cover areas of the study area from Chapter 1.

2.1.3 Quality habitat index.

To determine the degree of chimpanzee feeding habitat quality from the perspective of animals between vegetation classes we categorized the chimpanzee feeding habitat quality into two classes: 1) *general* feeding habitat quality, including all tree species known to be eaten by chimpanzees in western Tanzania irrespective of whether have being observed eaten at Gombe NP or not; and 2) *preferred-trees* feeding habitat quality, including the 30 tree species most frequently used by chimpanzees for food, calculated from the long-term Gombe database. The database includes all-day focal follows, with a continuous record of the focal chimpanzee's feeding behavior. The 30 most frequently eaten tree species comprised ~90% of all eating bouts recorded for tree species and over 80% of all recorded eating bouts in the Gombe chimpanzee database. To estimate total basal area of chimpanzee food for each vegetation class in the region, we used forest cover areas of the study area from Chapter 1.

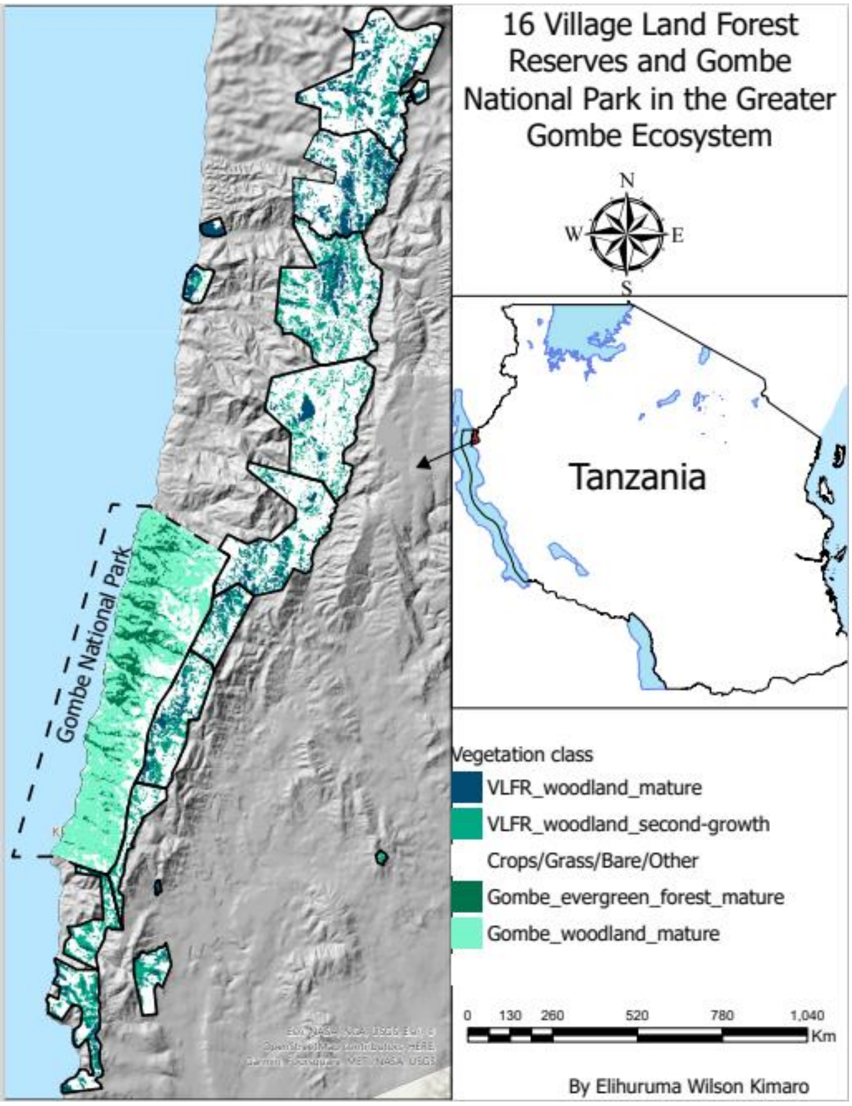

Figure 3.1: Vegetation classes in the village forest reserves and Gombe NP.

2.1.4 Human population and building densities.

We obtained human population size from the village government offices and calculated the density for each village as the number of people per square km. Since 4 out of 16 VLFRs (Kagunga, Zashe, Kiziba, and Bugamba VLFRs) are managed by more than one village, we calculated the weighted average of the population density for those VLFRs. We used the boundary length of VLFR for each village as weighing variable. To determine building density within VLFRs, we utilized point polygon building data extracted from 2005 Quickbird and 2017-2019 Maxar satellite images, using object based and Artificial Intelligence (AI) classification. Then LP converted the line polygons to point polygons. We sourced the building data from the JGI archived GIS and remote sensing datasets (Pintea, pers. comm.).

2.1.5 Forest monitoring effort.

We calculated forest monitoring effort as distance travelled (m) per day per ha as explained in Chapter 1.

2.1.6 Values of tree species to local people in the GGE.

We used a list of 22 of the tree species most frequently listed as important trees by the local people in the GGE published by Chepstow-lusty et al., (2006) to calculate the relative basal area for each vegetation class.

2.1.7 Plant functional traits.

We collected 5 seeds and 5 fruits per species at Gombe NP. We then determined the seed and fruit size by calculating the mean of seed and fruit length and diameter and weighing the dried seeds. For seeds and fruits that we did not find during field work we used information from the published literature. We assigned dispersal modes as (1) wind dispersal for seeds with wings, hairs, or plumes; (2) animal dispersal for seeds with fleshy pulp or aril; and (3) unaided dispersal for seeds with no clear dispersal adaptation (Lebrija-Trejos et al., 2010). We then calculated the Community Weighted Mean traits values (CWM) for each quantitative functional trait using basal area as the weighing variable (Alvarez et al., 2021). For the categorical trait of dispersal mode, we calculated the percent basal area per plot for each category (Alvarez et al., 2021).

2.1.8 Topographic factors.

We used an elevation raster with a spatial resolution of 10 m from the Gombe database developed by Pintea (2007), to calculate slope, aspect, and stream networks in ArcGIS Pro Geomorphometry and Gradient Metrics Toolbox.

2.2.0 Data analysis

Our main goals were: 1) to compare 7 forest attributes —basal area, stem density, above ground tree biomass, composition, carbon stocks, index of tree species perceived as important by local people, and chimpanzee feeding habitat quality— among plots that differed in forest type, forest age, and management status; and 2) assessing the relative influence of topographical and anthropogenic factors as well as tree functional traits. We sampled 257 plots but did not have sufficient representation in all factorial combinations of forest type (woodland or evergreen), age (young or old), or management class (VLFR or National Park). Thus, for aim 1 we analyzed subsets of our data to focus on three specific comparisons for all response variables: (i) for forest age we compared between the VLFRs mature woodland and VLFRs second-growth (young and intermediate aged) woodland, (ii) for management status we compared between the Gombe mature woodland and VLFRs mature woodland, and (iii) for forest type we compared between Gombe mature evergreen forest and Gombe mature woodland. For aim 2 we focused on VLFRs' forest inventory plots (Table 3.1).

2.2.1 Forest structure and composition

To determine observed species richness among vegetation classes we computed sample-based rarefaction and individual-based rarefaction for a comparable number of individuals (Dupuy et al., 2012). To estimate real species richness per vegetation class, we computed the Chao 2 estimator using *iNEXT* package (*v 3.0.0*) in R (4.1.0). To determine species diversity, we calculate Shannon Diversity Index H' using the formula $H' = -\sum p_i \ln(p_i)$, where p_i is the number of individuals of species *i* in each plot divided by the total number of individuals of all species in the plot. This index thus incorporates the species richness and the proportion of each species in all sampled plots (Goncalves et al., 2017). To analyze species composition, we computed the importance value index (IVI) for each vegetation class, adding their relative frequency, relative abundance, and relative basal area (Dupuy et al., 2011).

2.3.1 Statistical analysis

To determine the patterns in species composition of vegetation plots across vegetation classes we used Principal Coordinate Analysis (PCoA), based on the original abundance matrix data (Gabriel, 1971; Goncalves et al., 2016). The PCoA is an eigenvector-based method which reduces the multidimensionality of a dataset into a smaller number of dimensions, that summarizes the variability in the dataset allowing more flexible handling of complex ecological data (Huntley 2011; Goncalves et al., 2017). To test the differences of tree density, basal area, biomass, carbon stock, and chimpanzee habitat quality among vegetation types and forest management we used two-tailed t-tests (Jayakumar and Nair, 2013). To test the differences of these forest attributes among regenerating stages in VLFRs we used linear mixed model by including identity of village as a random effect.

To evaluate the relative influence of topography, stream networks, plant traits, and anthropogenic factors on biomass and stem density, we used an information-theoretic model selection approach (Burnham and Anderson, 2002), employing a set of multiple linear regression models, each intended to represent a hypothesis explaining the response variables. We ranked the models using the Akaike Information Criterion corrected for small samples (AICc) (Akaike, 1974). We used model selection in the *AICcmodavg* package in R (v 2.3-2) to calculate model-weighted parameters to understand the likely effect of each parameter in the models (Burnham et al., 2011). We interpreted explanatory variables whose model-averaged parameter estimate and 95% confidence intervals that exclude 0 as being significant. We controlled for village level effect in each model by including village identity as explanatory variable. In each model, we also control for forest age in each model. We used mature and second-growth woodland vegetation classes in the VLFRs for this analysis.

Features of the environment tend to be spatially autocorrelated, which makes the residuals of the model less independent (Gaspard et al., 2019). Therefore, we used Moran's I test in the *sdpep* package (*v 1.2-8*) in R (4.1.0) to test spatial autocorrelation among the models with the feature of the environment. If we detected spatial autocorrelation, we account it by fitting another linear model (Dormann, 2009; Crk et al., 2009). We performed eigenvectors mapping to capture spatial configuration. Then we include those eigenvectors that remove spatial autocorrelation in the model residuals into explanatory variables (Fischer and Nijkamp, 2014). To assess collinearity, we calculated the variance inflation factor (VIF). Then we eliminated predictors with VIF>3 (Carvalho et al., 2022).

2.3.2 Candidate model set.

To determine the relative influence of modifying variables—plant traits, topographic, and anthropogenic variables— on biomass and stem density in VLFRs, we specified 5 candidate models: 1) topography model which considered four factors: slope, aspect, elevation, and stream networks; 2) functional traits model, which considered three main factors, fruit size, seed size, and dispersal mode; 3) anthropogenic model, which considered four main factors, forest monitoring effort, distance of the plot to the lake Tanganyika, building density, and human population density; 4) forest patrols model controlling for topographic factors; and 5) global model which combine all factors we considered. In all models we controlled for forest age and village identity as a random effect.

3.0 Results

3.1 Patterns of composition by vegetation class

In all vegetation classes sampled we identified 159 tree species belonging to 44 families (Appendix III, Table 3.8 – 3.10). For adult trees (DBH>5cm) we recorded 94 tree species in VLFRs, which include mature and second-growth woodland. On the other hand, in Gombe NP (which include woodland and evergreen forest) we recorded 112 tree species with DBH > 5cm. The overall tree species diversity as measured by the Shannon Diversity Index (*H'*) was highest in the Gombe mature woodland (3.1) followed by the VLFRs mature woodland (2.5). The VLFRs second-growth woodland (2.2) had the lowest species diversity and was slightly lower than Gombe mature evergreen forest (2.3). Species-individual accumulation curve (rarefaction curve) calculated for equal number of individuals and Chao2 estimator, also showed that Gombe mature woodland has higher real species richness than other vegetation classes (Table 3.2, and Figure, 3.2).

Table 3.2: Observed and estimated species richness for all woody plants ≥ 5cm *dbh*.

Vegetation class	Total number of plots	Total number of stems	Observed number of species	Estimated number of species	95% CI (Chao 2)	% Richness (obs./est)
VLFR – second-growth woodland	75	3649	46	54.7	47.2-88.4	84.1
VLFR – mature woodland	102	4350	55	62.0	57.9-70.60	88.7
Gombe – mature woodland	49	1633	92	105.2	97.0-134.6	87.5
Gombe – mature evergreen forest	35	860	76	91.95	86.2-101.0	82.7

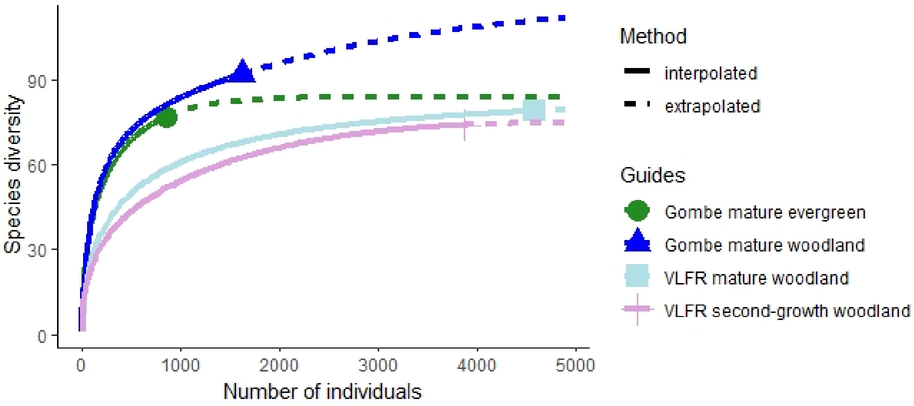

Figure 3.2: Rarefaction curve of different vegetation classes using all plots for a comparable number of individuals trees.

The IVI showed that *Brachystegia bussei* (Fabaceae) has the largest IVI in the VLFRs both in the mature and second-growth woodland forests, while *Diplorhynchus condylocarpon* (Apocynaceae) and *Croton sylvaticus* (Euphorbiaceae) have higher IVI in mature woodland and evergreen forest in Gombe NP, respectively. The VLFR second-growth woodland was dominated by *B. bussei* and *Julbenardia globliflora* (Fabaceae), which together represented 20% of the cumulative IVI. The VLFR mature woodland was dominated by *B. bussei,* accounting for 10% of the cumulative IVI. In contrast, no species attained 10 percent of the cumulative IVI in mature woodland and evergreen forest in Gombe, (Figure 3.3).

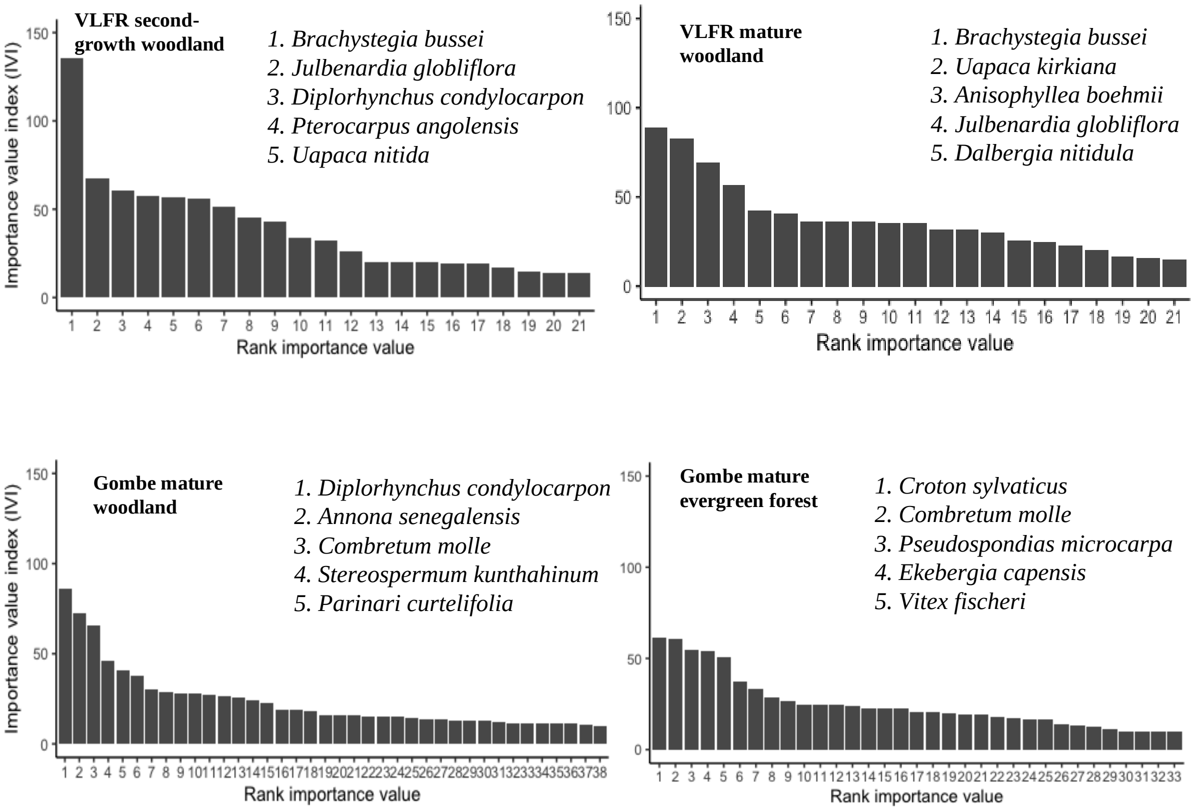

Figure 3.3: Importance value index (IVI) of those woody species that represented 80% of the cumulative IVI, listing the species with the highest IVI values in each vegetation class.

The first two PCoA axes explained 12.8% of the variation in species composition and showed considerable overlap among vegetation classes. The second-growth vegetation class comprises a subset of tree species shared by Gombe woodland and VLFR mature woodland vegetation classes, (Figure 3.4).

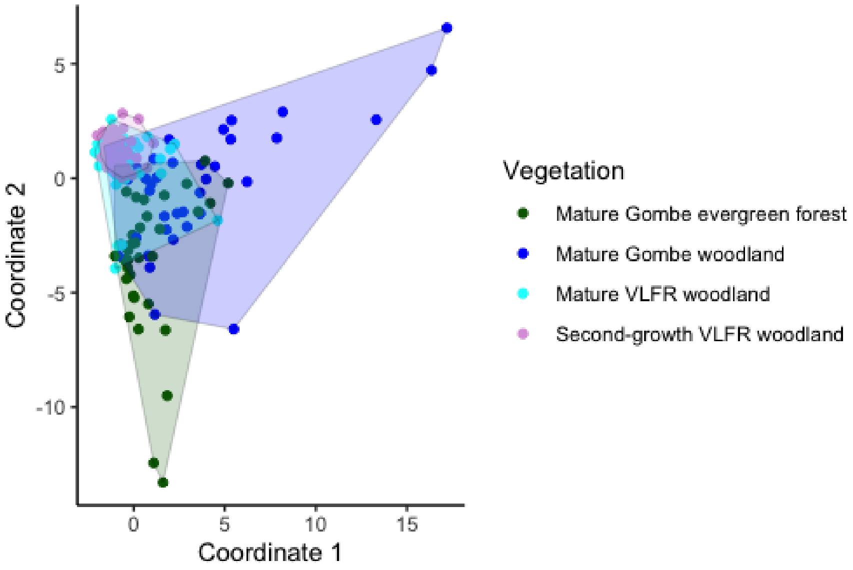

Figure 3.4: Principal Coordinates Analysis (PCoA) showing the relationship between the tree species composition and vegetation classes in the GGE. The first axis explained 12.8% of variation (Eigenvalue=1.5) and the second axis explained 5.6% of variation (Eigenvalue=1.3).

3.2 Patterns of forest structure and carbon stock.

We observed 9,899 stems with DBH >5 cm among all plots. The VLFRs contributed 85% of these stems. Many of the stems in the VLFRs fell into the 5–10 cm diameter range. In the mature woodland of the VLFRs, out of 4584 stems, 2976 stems (or 65%) have DBH values between 5 and 10 cm, while 3307 (or 85%) out of 3877 stems in the second-growth woodland in the VLFRs have DBH values between 5 and 10 cm. In Gombe, however, mature evergreen forest, 38 stems (about 7%) out of the 548 total stems have DBH between 5 and 10 cm. Similar to this, 47 (or 5%) of 890 stems in the mature woodland of Gombe have DBH values between 5 and 10 cm, (Figure 3.5).

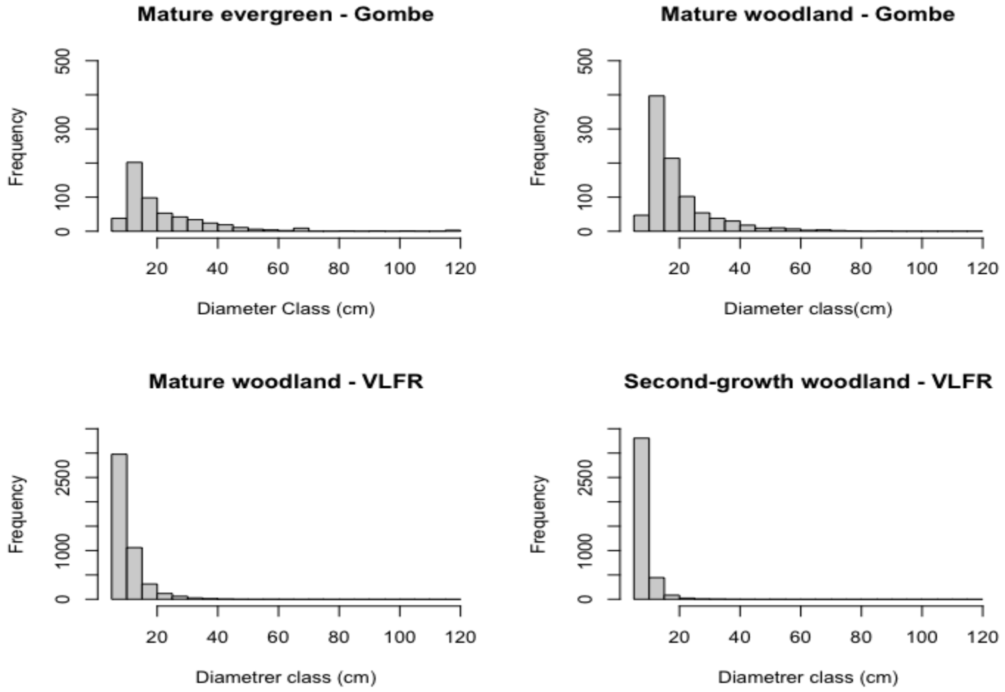

Figure 3.5: Stem diameter distribution across vegetation types. Compared to other classes, mature and second-growth woodlands in VLFRs have more stems in the 5 - 10 cm diameter class.

When we compared number of stems per ha between vegetation classes, we found that mature woodland in VLFRs had much lower stems per ha (1124 stems per ha) compared to the second-growth woodland (1301 stems per ha). However, the difference between the mature and second-growth woodland in VLFRs was not statistically significant ($p>0.05$). Also, mature woodland of VLFRs had higher number of stems per ha (1124) than the same forest type in Gombe (831 stem per ha). Likewise, mature woodland of Gombe had higher number of stems per ha (831 stem per ha) compared to mature evergreen forest (630 stems per ha). We found no significance difference for sapling and tree seedling between forest type, forest management, and forest age categories (Appendix III, Figure A3.2 &A3.3).

Moreover, the basal area and carbon stock (12.35 m^2 ha^{-1} and 34.02 Mg C ha^{-1} respectively) of mature woodland in VLFR were much higher than in second-growth woodland, which had a basal area of 8.06 m^2 ha^{-1} and a carbon stock of 18.06 Mg C ha^{-1}. Furthermore, mature woodland of Gombe had a larger basal area of 16.56 m^2 ha^{-1} and a higher carbon stock of 57.30 Mg C ha^{-1} than mature woodland of the VLFR, which had a basal area of 12.35 m^2 ha^{-1} and a carbon stock of 34.02 Mg C ha^{-1}. Although mature evergreen forest had a basal area of 17.89 m^2 ha^{-1} and a carbon stock of 69.10 Mg C ha^{-1} which were higher than in mature woodland in Gombe, the confidence interval overlapped (Figure 3.6 and Table 3.3).

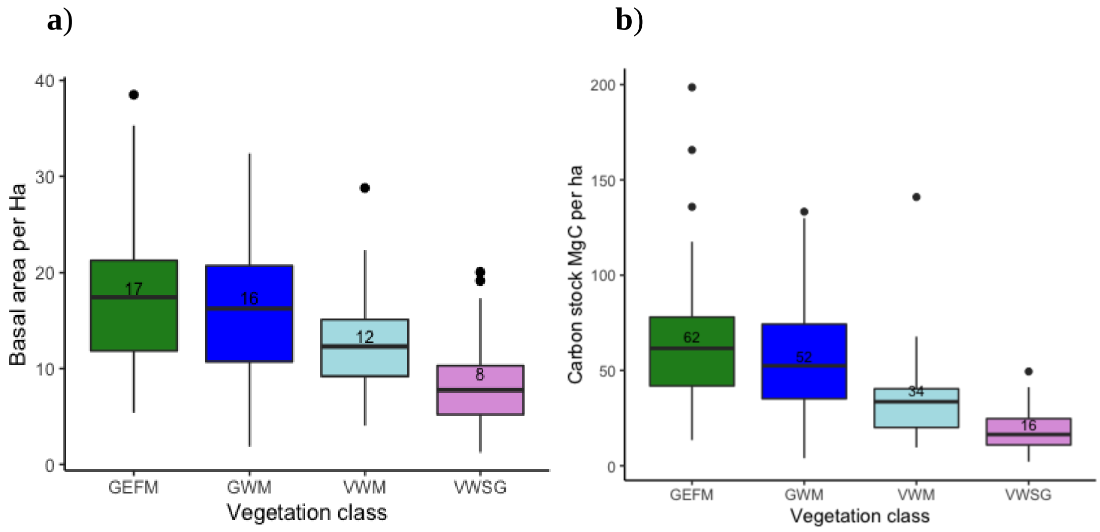

Figure 3.6: Boxplot showing the median differences in (a) basal area (m2ha-1) and (b) carbon stock (Mg C ha-1) across forest types (Gombe mature evergreen vs Gombe mature woodland), protected status (Gombe mature woodland vs VLFR mature woodland) and forest age class (VLFR woodland mature vs VLFR woodland second-growth).

Key: GEFM = Gombe mature evergreen forest, GWM= Gombe mature woodland, VWM= Village mature woodland, VWSG= Village second-growth woodland

Table 3.3: The mean tree aboveground carbon stock (Mg C ha^{-1}) and 95% Confidence Interval for different vegetation classes.

Vegetation Class	Year	Aboveground Carbon Mg C ha^{-1}	95% Confidence Interval
Gombe mature evergreen forest	2021	69.10	62.42 – 76.53
Gombe mature woodland	2021	57.30	51.64 – 62.98
VLFR mature woodland	2021	34.02	31.02 – 37.33
VLFR second-growth woodland	2021	18.06	16.34 – 19.80

3.3 Amount of total carbon stored in the study area.

The total carbon stored per vegetation class, calculated based on forest-cover areas and carbon stock per ha, indicated that second-growth woodlands sequestered approximately 37,230 Mg of carbon, which was about 77% of the carbon sequestered by mature woodlands (48,520 Mg) in VLFRs. Additionally, mature woodlands in Gombe sequestered the highest amount of carbon (134,443 Mg) compared to other vegetation classes (Figure 3.7, and see Appendix III, Table 3.3).

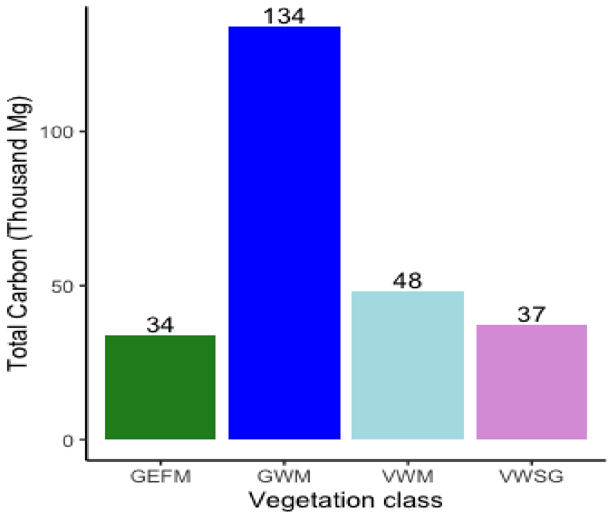

Figure 3.7: Total carbon in Mg using forest cover areas and carbon stock per ha of each vegetation class. The second-growth woodland has ~ 77 carbon stock found in the mature woodland of VLFRs. **Key:** GEFM = Gombe mature evergreen forest, GWM= Gombe mature woodland, VWM= VLFR mature woodland, VWSG= VLFR second-growth woodland, HBQ=Habitat quality

3.4 Chimpanzee feeding habitat quality.

Based on tree species composition for the *general* habitat quality, we found that, mature woodland in the VLFR has significantly ($p<0.0001$) higher basal area 11.06 m^2 ha^{-1} of chimpanzee tree food than second-growth woodland (7.40 m^2 ha^{-1}). Likewise, mature woodland of Gombe has significantly ($p<0.0001$) higher basal area of 14.74 m^2 ha^{-1} compared to mature woodland of VLFR (11.06 m^2 ha^{-1}). Furthermore, the basal area of chimpanzee tree food of mature evergreen forest of Gombe was 17.05 m^2 ha^{-1} and was higher than that of Gombe mature woodland (11.06 m^2 ha^{-1}). However, the difference between mature evergreen forest and woodland of Gombe was not statistically significant ($p>0.05$).

On the other hand, for the *preferred-tree* quality habitat, we found that vegetation classes within forest age and forest management categories were significantly different ($P< 0.05$). In the forest age category, the basal area of trees *preferred* by chimpanzees was higher in mature woodland in the VLFR (4.07 m^2 ha^{-1}) than in the second-growth woodland (2.52 m^2 ha^{-1}). Additionally, for the forest management category, mature woodland of Gombe has larger basal area of 5.97 m^2 ha^{-1} compared to mature woodland of VLFRs (4.07 m^2 ha^{-1}) (Figure, 3.8 and see Appendix III, Tables A3.1 & A3.2).

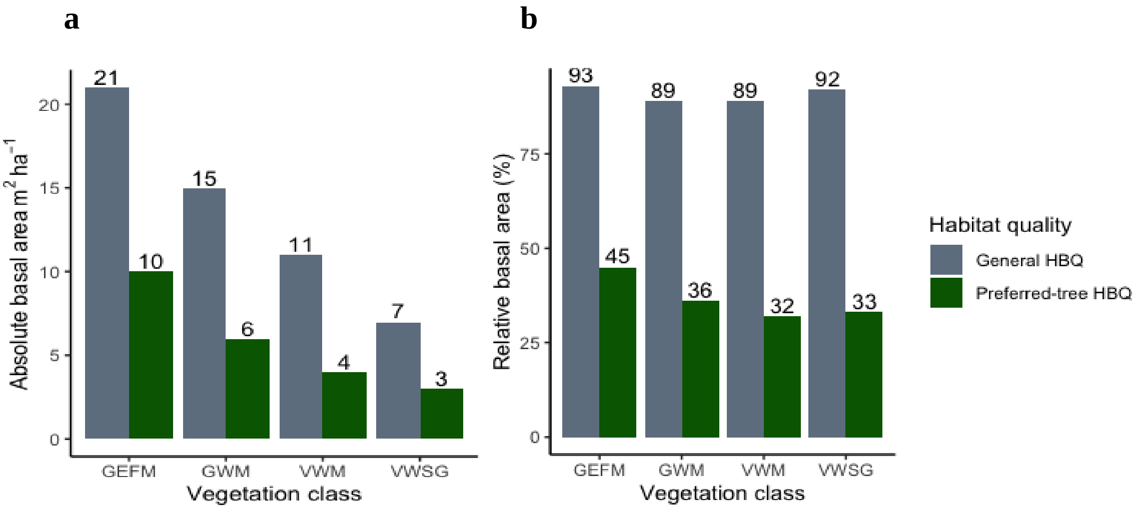

Figure 3.8: Absolute and relative basal area of tree species eaten by chimpanzees. Preferred tree habitat quality is approximately half of the general habitat quality across vegetation classes. Mature Gombe evergreen forest had the highest proportion of preferred habitat. a) Vegetation class level basal area of trees eaten by chimpanzees grouped as general and *preferred tree* habitat quality, **b)** Relative basal area of tree species eaten by chimpanzees grouped as *general and preferred tree* habitat quality.

Key: GEFM = Gombe mature evergreen forest, GWM= Gombe mature woodland, VWM= Village mature woodland, VWSG= Village second-growth woodland, HBQ=Habitat quality

3.5 Total basal area of chimpanzee food.

The total chimpanzee habitat quality per vegetation class, calculated based on forest-cover areas and basal area per ha of trees under the *general* and *preferred-tree* habitat quality categories, indicated that mature woodland of Gombe has higher total basal area (35200 m^2) of chimpanzee food than other vegetation classes in the GGE. We also found a minimal difference in total basal area of chimpanzee food between mature woodland of VLFRs (147,000 m^2) and the second-growth woodland (144,000 m^2), Figure 3.9.

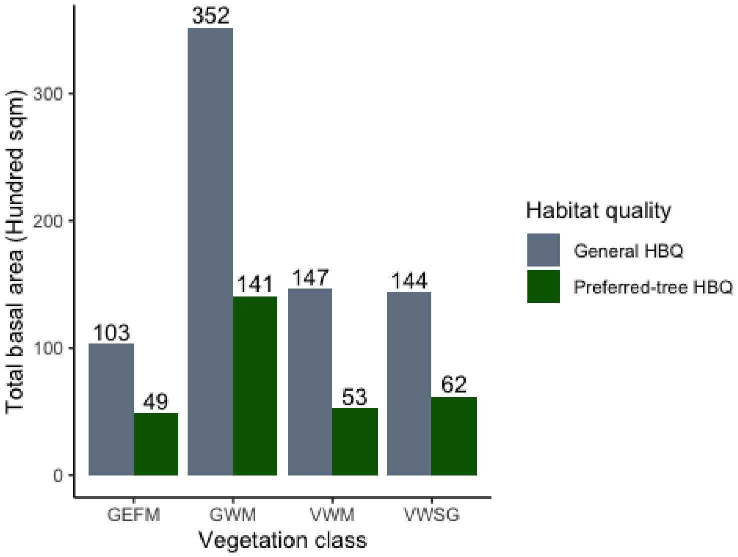

Figure 3.9: Total basal area of chimpanzee food for general and preferred trees habitat quality categories calculated using forest cover areas and basal areas per ha of each vegetation class. Key: GEFM = Gombe mature evergreen forest, GWM= Gombe mature woodland, VWM= Village mature woodland, VWSG= Village second-growth woodland, HBQ=Habitat quality

3.6 Patterns of trees highly valued by local people in the GGE

As we expected, we found that compared to Gombe NP, VLFRs have a higher percentage of species that the people consider to be valuable. The relative basal area of tree species highly valued by local people were 76% and 74% in mature and second-growth woodlands of VLFRs, respectively. In contrast, these tree species in Gombe had relative basal areas of 45% and 19% for mature woodland and evergreen forest, respectively. Additionally, we found that in mature and second-growth woodlands in VLFRs, of all tree species highly valued by local people, those used for firewood made up 52% and 60% of the basal area, respectively. In Gombe NP however, majority of tree species highly valued by the local people are those used for multiple purposes (more than three purposes), (Figure 3.10).

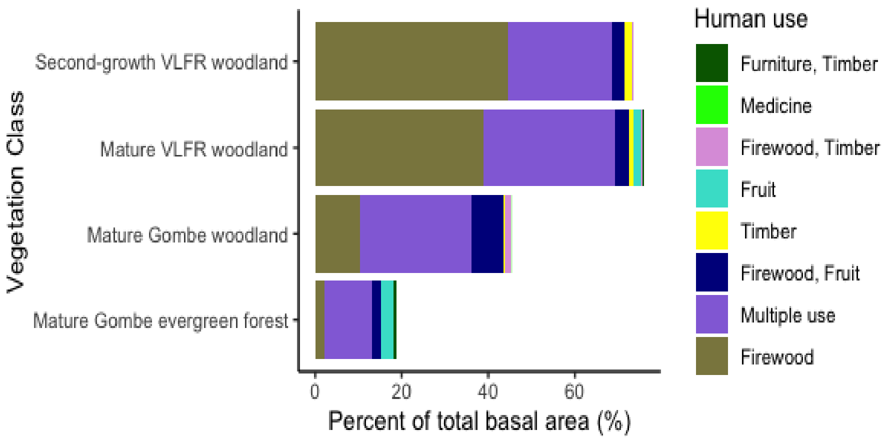

Figure 3.10: Compared to Gombe, VLFRs have a higher proportion of tree species that the local people consider valuable. Most of the tree species highly valued in VLFRs and Gombe are those used for firewood and for multiple use, respectively.

3.6 The effects of topography, stream networks, plant functional traits, and anthropogenic factors on the variation of tree biomass.

We did not detect a signal of spatial autocorrelation in the residuals of models with biomass as a response variable. We did, however, detect a signal of spatial autocorrelation in the residuals of models that included topographic parameters with stem density as a response variable. We also excluded two parameters, distance from the lake and animal dispersal mode, as they had VIF>3. The model that included patrols and topographic parameters largely explain (w_i= 0.64) the variation of stem density than anthropogenic and plant functional traits. Furthermore, the model that included plant functional traits—dispersal mode, seed weight, and fruit diameter—explained the variation of tree biomass (w_i= 0.66) better than anthropogenic model (w_i= 0.30). In favor of our prediction, we found a trend that forest patrols positively influenced the stem density (β = 828, 95% CI: [(320, 1333)]) and the tree biomass (β =1.46, 95% CI: [-0.93, 9.94]). However, the 95% CI of the influence of patrols on tree biomass include zero. In addition, distance to stream and seed weight positively influence tree density, while forest age and unaided dispersal positively influence biomass. Although human population density and building density have negative influence on tree density and biomass the estimates included zero in 95% CI, (Figure 3.11, and Tables 3.4 & 3.5).

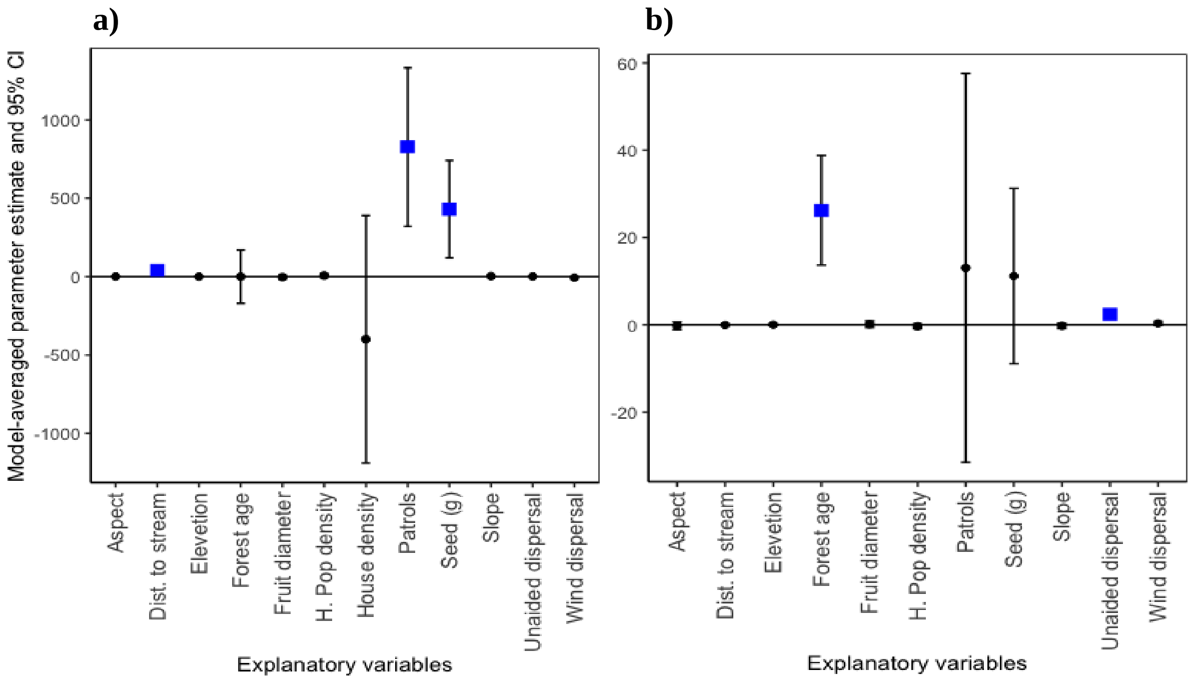

Figure 3.11: Summary of model-averaged parameter estimates and their 95% confidence interval in the VLFRs: a) for variation of stem density, village-led patrols and seed weight have higher positive effect, b) for variation of tree biomass**,** forest age and unaided dispersal mode have positive effect.

Table 3.4: Summary of model selection: variation of the adult tree biomass in the VLFRs.

Factors	**Plant trait**	**Human**	**Global**	**Topography + patrol**	**Topography**	**MAP**	**2.5%**	**97.5%**
Yi	2.39	157	126	-80.3	11.3	48.01	-186.4	282.4
Distance to stream			-0.03	-0.04	-0.03	-0.03	-0.11	0.04
Slope			-0.27	-0.12	-0.16	-0.21	-0.81	0.38
Aspect			-0.03	-0.003	0.007	-0.18	-1.05	0.68
Elevation			0.05	0.04	0.02	0.04	-0.02	0.1
Patrols		11.9	14.22	37.6		13.05	-31.52	57.61
Wind dispersal	0.31		0.41			0.32	-0.16	0.8
Self-dispersal	0.41		0.46			0.41	0.14	0.68
Fruit diameter	-0.2		-0.1			0.14	-0.6	0.9
Seed (g)	11.2		11.16			11.18	-8.91	31.26
Human density		-0.31	-0.41			-0.32	-0.84	0.2
Mature woodland	24.9	33.6	33.4	36.0	34.6	26.2	13.7	38.8
K	**19**	**17**	**25**	**20**	**19**			
Δ AICc	**0.00**	**1.56**	**6.50**	**7.83**	**9.44**			
w_i	**0.66**	**0.30**	**0.03**	**0.01**	**0.01**			

Key: Global = anthropogenic + plant trait + topography; Yi= intercept.

Table 3.5: Summary of model selection: variation of stem density in the VLFRs.

Factors	**Topography + patrol**	**Topography**	**Human**	**Global**	**Plant trait**	**MAP**	**2.5%**	**97.5%**
Yi	-693	1324	-1126	-1394	1314	40.25	-2323	2404
Distance to stream	1.49	1.59		1.19		1.53	0.49	2.57
Slope	3.52	2.87		3.57		3.29	-4.6	11.17
Aspect	0.76	1.02		0.53		0.86	-0.07	1.79
Elevation	0.40	-0.04		0.17		0.24	-0.6	1.11
Patrols	829		-1286	-404.9		828.6	320.3	1333
Wind dispersal				-6.28	-7.05	-6.68	-13.95	0.6
Self-dispersal				0.54	1.81	1.2	-3.08	5.48
Fruit diameter				-3.9	-2.3	-3.1	-16	10
Seed (g)				390	469	430	120	741
House density				-666	-352	-399.5	-1189	390
People density				10.4	6.24	6.87	-5.75	19.48
Mature woodland	0.31	0.19	-44	25.3	29.8	0.27	-170	170
K	**24**	**24**	**17**	**25**	**18**			
Δ AICc	**0.00**	**1.12**	**25.4**	**28.9**	**29.3**			
w_i	**0.64**	**0.36**	**0.00**	**0.00**	**0.00**			

Key: Global = Human activities + plant trait + topography; Yi= intercept

4.0 Discussion

As human-modified landscapes become the most common scenario in Africa and elsewhere in the tropics, the future of tropical biodiversity largely depends on our ability to preserve it in these landscapes (Muench and Martinez-Ramos, 2016). The successful conservation of tropical biodiversity, therefore, requires both strictly protected areas, such as national parks and means of ensuring the protection of biodiversity outside these protected areas (Hocking et al., 2015). Community conservation approaches have the potential to advance forest conservation and restoration efforts outside strictly protected areas (Marshall, 2009; Vihemaki and Leonard, 2010; Muench and Martinez-Rams, 2016; Edward et al., 2020). Despite this potential, few studies have evaluated their influence on species survival and climate change mitigation. In this study we used established ecological knowledge of the positive change of seven forest attributes to assess the influence of VLFRs on forest recovery and persistence. Once we considered this critical information, we evaluated the relative influence of other crucial factors, including topography, tree functional traits, and anthropogenic factors on forest structure in these VLFRs.

Our analysis of 257 forest inventory plots in these VLFRs and Gombe NP confirms that VLFRs can promote the persistence and recovery of important forest attributes, including forest structure, composition, carbon stock, and quality habitat for primate species. Our key findings were as follows: a) reserves on village land have demonstrated the capability of promoting the rapid recovery of essential forest attributes. Specifically, in ~15 years the second-growth woodland has sequestered ~half of the carbon stock per ha and has attained about two-third of chimpanzee habitat quality found in mature woodland in VLFRs; b) due to the large area covered by VLFRs in the GGE, VLFRs can store substantial amounts of carbon at regional scale, and that as forests and woodlands in these reserves become permanent—are not cleared again— their capacity to store carbon will increase; c) Gombe forests, not surprisingly, exhibit more mature traits than VLFRs, as witnessed by their lower stem density and greater basal area; d) The woodland of Gombe demonstrated an impressive ability to maintain forest attributes, often reaching levels comparable to those observed in evergreen forests. Although the index of *general* quality habitat for chimpanzees in Gombe mature evergreen forest was 14% greater than that of Gombe mature woodland the confidence interval overlapped. This signal important information on the capacity of woodlands in the GGE to restore and maintain chimpanzee feeding habitat quality. Therefore, if well protected, woodland of VLFRs can provide substantial amounts of food for chimpanzees and other wildlife in the GGE, thus contributing to landscape-scale connectivity; and e) patrolling by VFMs have a positive influence on stem density and biomass. This suggests the importance of this activity in ensuring sustainability of VLFRs in the GGE.

4.1 Patterns of forest and woodland composition.

The woodlands in VLFRs and Gombe NP are primarily characterized by tree species commonly found in miombo woodland across eastern, southern, and central Africa (Goncalves et al., 2016). Although the VLFRs contain ~83% of taxa found at Gombe NP, the relative abundance of tree species varied among land-cover types. In Gombe mature woodland, dominant species include *Diplorhynchus, condylocarpon* (Apocynaceae), *Annona senegalensis* (Annonaceae), and *Combretum molle* (Combretaceae) while in Gombe mature evergreen forest, the dominant tree species include *Croton sylvaticus* (Euphorbiaceae), *Combretum molle*, and *Pterocarpus macrocarpa* (Anacardiaceae). These dominant species are typically associated with more established and less disturbed forest ecosystems (Clutton-Brock and Gillett, 1979; Gondwe et al., 2020). Interestingly, many of these species are among the 30 most eaten tree species by chimpanzees. On the other hand, although some of the dominant tree species in the VLFRs include those 30 most eaten tree species by chimpanzees, the majority of the dominant tree species in VLFRs are those perceived as important by the people in the villages. These tree species are *Brachystegia bussei* (Fabaceae), *Uapaca kirkiana* (Euphorbiaceae) and *Anisophyllea boehmii* (Anisophyleaceae) for mature woodland and *Brachystegia bussei,* and *Julbenardia globiflora* (Fabaceae) for second-growth woodland of VLFRs. Most of these tree species are associated with early woodland recovery (Gondwe et al., 2020). This suggests that most of the tree species that chimpanzees prefer are later successional species while those which people in the village prefer are earlier successional species.

As a whole, we recorded 159 tree species belonging to 44 families. The Shannon Diversity Index scores ranged from 2.2 – 3.1. These scores are similar to scores found in forest and woodland ecosystems in Tanzania (Jew et al., 2016). The Shannon diversity index of Gombe mature woodland exceeds that of other vegetation types. The rarefaction curve also shows that Gombe mature woodland has higher species richness. However, the curve was not saturated, suggesting incomplete sampling depth. As Gombe mature woodland makes up a large portion of Gombe's forest, it may explain why Gombe mature woodland has more species than Gombe evergreen forests. Mature woodland in Gombe makes up 72% of forest cover in Gombe. Ecologically, this tendency has been observed at other locations as well: a larger area is likely to support a greater variety of species (Saura, 2020).

4.2 Patterns of forest structure and carbon stock.

The structure of forest and woodland ecosystems can be quantified by examining the density of trees. Tree densities in African forests and miombo woodlands range from 380 to 1400 trees ha^{-1}, according to earlier studies (Frost, 1996). The results of this study followed a similar pattern, with a median value of 978 trees ha^{-1} and a range of 617 to 1300 trees ha^{-1}. We found that VLFRs have higher tree density than Gombe, but lower basal area. Moreover, in VLFRs, more than 70% of trees fall into 5-10 cm diameter category, whereas fewer than 7% of trees species in Gombe fall into this category. Collectively, these results indicate that the forests in VLFR are in earlier successional stages compared to that of Gombe NP. This is not surprising, as VLFRs in the GGE have only been under protection since 2006 and the secondary forests are expected to be younger. It is also likely that even the mature woodlands on village land have long been subject to continued human disturbances such as tree cutting for firewood and timber.

The increased density of trees in the second-growth woodland of VLFRs compared to other vegetation types may be attributed to two factors. First, the older forests are undergoing self-thinning and thus have lower stem densities, but higher average diameters (Westoby, 1984). Second, many woodland species are able to regenerate quickly, sprouting from tree stumps, and enjoying less competition for light and space in their more open habitats (Gumbo et al., 2018). This may also explain why the second-growth woodland in the VLFRs was able to recover ~50% of the carbon stock per ha found in mature woodland in VLFRs after only ~15 years. However, mature woodland in VLFRs still have lower carbon stock per ha compared to mature woodland of Gombe, suggesting that mature woodlands in VLFRs are still regenerating and have potential to store more carbon. Compared to other miombo woodland ecosystems, the estimate of carbon stock in mature Gombe woodland —57.30, 95% CI: [51.64, 62.98] Mg C ha^{-1}—falls in the upper range of old-growth miombo woodland ecosystems in Africa (Bulusu et al., 2021). Importantly, the estimate of carbon stock in mature woodland in VLFRs—34.02, 95% CI: [31.02, 37.33] Mg C ha^{-1}—falls within the range previously seen in mature woodland ecosystems in Africa (Gumbo et al., 2018). Therefore, VLFRs in the GGE region have already sequestered a sizable amount of carbon and have the potential to sequester more carbon when adequately protected.

Generally, woodlands store less carbon per ha than evergreen forests (Munishi and Shear, 2004; Shirima et al., 2015). Our findings showed that, although mature evergreen forests in Gombe NP have 17% higher carbon stock per ha than mature woodland in Gombe, the confidence intervals overlap. This demonstrates the potential of woodland in the ecosystem with evergreen forests to store carbon per ha, sometime at a comparable level with evergreen forests (Frost, 1996). Our data on VLFR's carbon storage potential are also encouraging. They suggest that VLFR, if protected for a long time, have the potential to store a substantial amount of carbon—to a comparable level of Gombe mature woodland, which is critical for climate change mitigation.

4.3 Feeding habitat quality for primate species.

Our findings showed that the second-growth woodland has almost two-thirds of the habitat quality per ha of the mature woodlands in VLFRs. Likewise, mature woodland in VLFRs has a habitat quality per ha nearly two-thirds that of mature woodland in Gombe. This indicates the capacity of VLFRs in the GGE to quickly recover and preserve feeding habitat quality for primates and other animal species, even though many of the VLFR tree species are also favored by people (Figure 3.10). In addition, Gombe evergreen forest has ~14% higher quality habitat per ha than Gombe mature woodland, however, the 95% confidence intervals for the two forest categories overlapped. This signals the potential of woodlands in VLFRs in the GGE to offer quality habitat for primate species, when protected for a long time like those of Gombe. Therefore, to ensure sustainability, more effort is needed to encourage and improve the effective management of these reserves, dominated by miombo woodlands. As miombo woodland in Tanzania covers about 93% of all forest land (Manyanda et al., 2020), to be effective, primate conservation plans should include woodland regeneration strategies as a key to achieving success.

4.4 The effect of topography, plant functional traits, and anthropogenic factors on the variation of tree biomass and stem density.

Since many forests and woodlands are found outside protected areas (FAO, 2020) largely in mosaic landscapes (Edwards et al., 2019), strategies that ensure their persistence are needed. This includes understanding how multiple factors influence biodiversity patterns in human-modified landscapes (Arroyo-Rodriguez et al., 2017). In this study, we evaluated the relative contributions of anthropogenic, topographical, and functional plant traits to the variation in tree biomass and stem density in VLFRs of the GGE. Our results showed that a combination of human activity and topographical factors largely explain the variation in stem density while plant functional traits model, which include dispersal mode, fruit diameter, and seed weight, largely explain the variation in tree biomass.

Meanwhile, proximity to streams promotes plant growth and regeneration. However, in our study we found that stem density was positively correlated with distance from streams. Human activities, such as agriculture, may have contributed to this. As people cultivate crops, such as maize and beans, they look for areas with dependable water sources. Therefore, areas closer to streams are attractive for farming because they have higher soil moisture than other areas, making them more susceptible to agricultural activities. Proximity to streams, however, favored tree biomass, although estimates included zero at 95% CI. This may suggest that as people clear areas for agriculture they leave some large trees for shelter and other reasons.

More topographic complex landscapes, such as those in GGE, are more susceptible to soil erosion. Tree cutting for agriculture and other human activities exacerbate this issue. This in the end creates poor soil. In such stressful conditions, larger seeds are more likely to germinate and establish than smaller seeds (Mao et al., 2019). Relatively large seeds, therefore, can improve the germination and seedling tolerance of tree species in such conditions, as they have more nutrients than light seeds. This can help explain our findings on the positive influence of seed weight on stem density.

Moreover, the significant positive influence (β=0.41, 95% CI: [0.14, 0.68]) of unaided or explosive dispersal mode on biomass in VLFRs is primarily due to the influence of legume plants. Legumes are very abundant, and many have this dispersal mode (Gei et al., 2018). The dominant tree species, *Brachystegia species, and J. globiflora* are legume plants. In addition to sprouting from stumps, legume seeds germinate rapidly after a rainy season: the legume seedlings also grow relatively quickly (Vargas et al., 2015). Also, some legume plants can work in symbiosis with bacteria that absorb nitrogen from the air (N_2) and convert it for use by plants (Gei et al., 2018). As a result, legumes have an advantage in dry environments, like these reserves.

On the other hand, patrols performed by VFMs influence positively the stem density. This shows that patrols are protecting/promoting young forest to grow and provide a promising indication that with improved patrolling, likely VLFRs will promote fully recovery of forest in the GGE. The strong positive influence of forest patrols on stem density (β =828, 95% CI: [(320, 1333)]) in the GGE, indicates that locals, in most circumstances, are crucial to the success or failure of communally managed forests. In the end, they are the ones who determine the fate of their reserves through their decisions (Ehrlich and Sodhi, 2011; Edwards et al., 2019; Goodall et al., 2022).

Conclusion

In our study, we examined 4 main questions: forest age (mature versus second-growth woodland in VLFRs), forest management (mature woodland of VLFRs versus mature woodland of Gombe), and forest type (mature woodland versus mature evergreen forest in Gombe) questions as well as influence of other factors on the variation of tree biomass and stem density. We found that woodlands of VLFRs can rapidly recover essential forest attributes. In ~15 years second-growth woodland has sequestered ~half of the carbon stored in mature woodland. The second-growth woodland also has ~ 83% of tree species found in the mature woodland. This fast recovery maybe attributed by the ability of woodland to sprout from stumps and the availability of seeds from remnant forest patches in these reserves. Although VLFRs have shown a remarkable ability to recover forest attributes, the mature woodlands in these reserves showed signs of being at a younger successional stage than those found in Gombe NP. The mature woodland in VLFRs has lower basal area, biomass, basal area of chimpanzee food, and carbon stock, but higher stem density compared to the same forest type at Gombe NP. Surprisingly, our findings contradicted our initial expectations. Despite observing higher values in mature evergreen forest, the measures of forest structure, composition, carbon stock, and chimpanzee habitat quality overlapped with those of mature woodland in Gombe National Park. This suggests the capacity of miombo woodlands of the

GGE to promote the growth and preservation of these forest attributes. Therefore, with adequate protection, woodlands in VLFRs may promote landscape-scale connectivity, sequester substantial amount of carbon, and enhance ecosystem services to people in the GGE.

Despite the challenges involved in managing these reserves, forest patrols by village forest monitors appear to promote recovery and persistence of forest structure in these reserves. Therefore, we strongly recommend implementing plans to improve and support village forest monitors' activities as this is crucial for enhancing reserve management. In doing so, the VLFRs should be able to recover and preserve woodlands in the GGE, aligning with Tanzania's commitment to restore over 5.2 million ha of land under The Bonn Challenge within the African Forest Landscape Restoration Initiative (AFR 100) by 2030 (Owusu et al., 2021). This alignment will contribute significantly to forest conservation and restoration efforts in the region.

General Conclusion

Overall, this dissertation reveals evidence of success for community-managed conservation in the GGE. Satellite imagery demonstrated a 66% increase in forest cover between 2006 and 2021 within the VLFRs, in sharp contrast to a 22% forest cover decrease on unprotected village land. The forest inventory data revealed that the regenerated and mature woodlands in the VLFRs harbor a substantial number of tree species, with about 80% of the tree species found in Gombe NP, and a higher stem density per ha than Gombe NP. This suggests that forests in VLFRs are much younger than Gombe NP. Nonetheless, these reserves store a considerable amount of carbon and provide a substantial amount of food for primates. Compared to mature woodlands in Gombe NP, mature woodlands in VLFRs store ~75% of carbon per ha and maintain ~75% of chimpanzee habitat quality per ha. Moreover, compared to mature woodland in the VLFRs, second-growth woodland recovered ~50% of carbon stock per ha and ~67% of chimpanzee habitat quality per ha. This suggests that forests in VLFRs are rapidly growing and have the potential to reach the forest characteristics of mature woodland found in Gombe NP. However, challenges remain.

One of the main risks to VLFRs is the clearing of mature and second-growth forests due to human activities. The study found that of the forests that regenerated between 2006 and 2013, ~11% were subsequently cleared between 2013 and 2021. Additionally, of the forest within these reserves that existed in 2006, ~ 32% was cleared between 2006 and 2021. Fire regimes associated with charcoal production and swidden agriculture were among the factors that negatively influenced forest cover change in these reserves. The majority of these human threats likely result from people living inside these reserves. Higher building density inside these reserves, which is a proxy for human population density, negatively impacts forest cover change. Relocating people residing within these reserves or providing them with the appropriate incentives to voluntarily leave would significantly contribute to forest and wildlife conservation in the GGE.

Furthermore, the tree species valued by villagers constitute a substantial portion — 75%—of the basal area of all adult tree species in VLFRs, with more than 50% of the tree basal area being species favored for firewood. If VLFRs are properly managed, these predominantly pioneer species will eventually be replaced by later successional species, most likely resembling species found in Gombe NP. The majority of dominant tree species in Gombe NP include tree species that are commonly eaten by chimpanzees as a food source. This includes *Diplorhynchus condylocarpon, Annona senegalensis, Pseudospondias macrocarpa, Vitex fischeri,* and *Parinari curtelifolia*. Therefore, as forests in VLFRs develop they have the potential to provide high-quality habitats for chimpanzees and other wildlife. This necessitates more forest patrols as they appear to promote forest growth by reducing human threats in these VLFRs. Expanding conservation efforts in these reserves will enhance landscape-scale connectivity, biodiversity conservation, and climate change mitigation in the GGE.

While community forest conservation aims to deliver multiple benefits, including promoting forest conservation and reducing rural poverty (Duguma et al., 2018), this dissertation focuses on forest conservation. The study, therefore, recognizes the need for further assessment to understand the contribution of these reserves to human well-being. Nevertheless, I believe that the successful recovery and protection of forest resources in these reserves have likely already benefitted communities through reduced soil erosion, persistent streams from catchment forests, and other ecosystem services like crop pollination by forest-dwelling insects and birds.

Also, by demonstrating the extent of success in protecting forest resources, this dissertation lays a strong foundation for assessing the potential contributions of community forest conservation to the reduction of rural poverty in the GGE. Future research can also explore suitable economic options for communities in the GGE. This includes how communities can benefit from the reduced emissions from deforestation and forest degradation (REDD) framework under the Paris Agreement. People in developing countries can receive results-based payments for reducing deforestation under the REDD initiative (FAO, 2022), encouraging further forest protection in the region.

Despite the remote and complex topographic terrain of the GGE, human activities still impact most of these reserves, posing challenges to their regeneration and persistence. This is not unique to the GGE. In Tanzania’s eastern arc mountains, one of the global hotspot areas, VLFRs face similar threats: agricultural encroachment, fire, charcoal production, timber extraction, and habitat fragmentation (Burgess et al., 2007). Thus, implementing monitoring and capacity building programs like the ones JGI is implementing in the GGE will improve forest management in these reserves. However, many communities find this investment challenging because it involves substantial resources. This necessitates strategies to meet local communities' limited financial and technical capacities to ensure sustainability of VLFR programs.

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Appendix for Chapter 1:

Supplementary Information (SI)

Community-managed forests promote forest cover increase in the human-modified landscape of the Greater Gombe Ecosystem, Tanzania.

Methods

Image processing

Image preprocessing steps include image registration, radiometric calibration, atmospheric correction, and topographic correction (Phiri & Morgenroth, 2017). We performed image registration by transforming images into one coordinate system (Keshtkar et al., 2017). For the Landsat datasets, we downloaded radiometrically corrected and orthorectified surface reflectance images (collection 2-level 2-products) from the USGS website. For the RapidEye images, we purchased and downloaded the radiometrically corrected and orthorectified surface reflectance images from the APOLLO mapping website and mosaicked them into a single scene. For the SPOT images, we purchased and downloaded the raw images from the APOLLO mapping website. We processed the SPOT images using PCI Geomatica software. We used a Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) and ground control points selected from Google Earth to orthorectify the panchromatic and 4-band multispectral images. Then we pan-sharpened them to a 4-band 1.5m image with 16-bit depth.

Radiometric Normalization

To reliably compare land-cover changes from multi-temporal multi-sensor satellite images, a common radiometric signature of the ground reflection is required (Gan et al., 2021). We acquired the remote sensing datasets at different times and with different sensors. The most common normalization process —the relative radiometric normalization method — involves using one image as a reference and adjusting the radiometric properties of the other images to match the reference (Gan et al., 2021). This process makes the normalized images look as though they were acquired with the reference image sensor under illumination and atmospheric conditions same as the reference scene (Hall et al., 1991).

Since the 2013 Landsat scene had a minimum distance from other images, we used the 2013 Landsat scene as a reference image. To perform radiometric resolution. To normalize the target images to the reference image — the 2013 Landsat dataset — we performed Major Axis regression analysis in *R (4.1.0)* (Legendre, 2008).

We did not perform normalization process for the SPOT and RapidEye images. This would require us to first degrade the resolution from 1.5 m and 5 m for SPOT an RapidEye scenes to 30 m resolution to match that of Landsat resolution. Degrading the resolution always involve data loss. The use of machine-learning models such as Random Forest with the same training samples between the images may reduce the need for performing radiometric normalization (Helmer, 2010). Therefore, we also used the same training sample to separately classify both images for each year i.e., using the same training samples for both Landsat and SPOT scenes for the year 2016 and the same training samples for both Landsat and SPOT for the year 2021. Also, we used the same training samples to train both the 2011 RapidEye and 2013 Landsat scenes. For consistency, we only used the results of the classification process of the high-resolution imagery to support the Landsat classification process.

Table A1.1: Land cover training samples

Land cover	Number of training pixels of Landsat	Number of training pixels of SPOT	Number of training pixels of RapidEye
Evergreen forest	1,885	12,600	1,890
Woodland	19,600	130,200	19,530
Oil palm	3,994	27,958	4,193
Unclassified land	25,742	180,194	27,029

Table A1.2: Characteristics of image used in preparation of mask layer.

Imagery	Acquisition Date	Spatial Resolution (m)	No. of Bands	Path/Row	Source
Landsat 5	20 June 1984	30	7	172/63	USGS

Table A1.3: Total area analyzed in each location.

S/No	Location	Area in km^2
1	Village Land Forest Reserves	93.37
2	Gombe National Park	35.65
3	Unprotected village land (sample)	61.18

Table A1.4: The summary of the classification accuracy test for the Landsat, RapidEye, and SPOT scenes

Year	Satellite	Overall Accuracy
2006	Landsat	89.11%
2011	RapidEye	93.28%
2013	Landsat	87.84%
2016	Landsat	87.89%
2016	SPOT	95.92%
2021	Landsat	88.61%
2021	SPOT	95.02%

Table A1.5: Cross-tabulation error matrix of classified Landsat image versus reference data for 2006

Classified image	**Reference Data - 2006**			
	Forest &Woodland	*Unclassified*	*Oil Palm*	*Row totals*
Forest & Woodland	0.390	0.038	0.009	0.438
Unclassified	0.028	0.463	0.003	0.494
Oil palm	0.019	0.012	0.039	0.069
Column totals	0.437	0.513	0.050	1
User’s accuracy	89%	93%	55%	
Producer’s accuracy	89%	90%	77%	
Total accuracy		89.11%		

Table A1.6: Cross-tabulation error matrix of classified Landsat image vs. reference data for 2013

Classified image	**Reference Data - 2013**			
	Forest &Woodland	*Unclassified*	*Oil Palm*	*Row totals*
Forest & Woodland	0.404	0.027	0.013	0.444
Unclassified	0.031	0.447	0.003	0.481
Oil palm	0.035	0.013	0.027	0.075
Column totals	0.469	0.487	0.043	1
User’s accuracy	91%	92%	37%	
Producer’s accuracy	86%	92%	64%	
Total accuracy		87.84%		

Table A1.7: Cross-tabulation error matrix of classified Landsat image v reference data for 2016

Classified image	**Reference Data - 2016**			
	Forest &Woodland	*Unclassified*	*Oil palm*	*Row totals*
Forest & Woodland	0.317	0.030	0.012	0.359
Unclassified	0.048	0.533	0.001	0.581
Oil palm	0.027	0.002	0.029	0.586
Column totals	0.392	0.566	0.042	1
User's accuracy	88%	92%	49%	
Producer's accuracy	81%	94%	69%	
Total accuracy		87.89%		

Table A1.8: Cross-tabulation error matrix of classified Landsat image versus reference data for 2021

Classified image	**Reference Data - 2021**			
	Forest &Woodland	*Unclassified*	*Oil palm*	*Row totals*
Forest & Woodland	0.355	0.035	0.025	0.415
Unclassified	0.022	0.492	0.003	0.517
Oil palm	0.027	0.001	0.039	0.068
Column totals	0.403	0.529	0.068	1
User's accuracy	85%	95%	58%	
Producer's accuracy	88%	93%	58%	
Total accuracy		88.61%		

Table A1.9: Cross-tabulation error matrix of classified SPOT image versus reference data for 2016

Classified image	**Reference Data - 2016**			
	Forest &Woodland	*Unclassified*	*Oil palm*	*Row totals*
Forest & Woodland	0.338	0.018	0.007	0.352
Unclassified	0.008	0.588	0.001	0.597
Oil palm	0.006	0.002	0.043	0.051
Column totals	0.342	0.608	0.051	1
User's accuracy	93%	99%	85%	
Producer's accuracy	96%	97%	85%	
Total accuracy		95.92%		

Table A1.10: Cross-tabulation error matrix of classified SPOT image versus reference data for 2021

Classified image	**Reference Data - 2021**			
	Forest &Woodland	*Unclassified*	*Oil palm*	*Row totals*
Forest & Woodland	0.325	0.025	0.007	0.357
Unclassified	0.009	0.583	0.001	0.593
Oil palm	0.006	0.002	0.043	0.050
Column totals	0.340	0.610	0.050	1
User's accuracy	91%	98%	85%	
Producer's accuracy	96%	96%	85%	
Total accuracy		95.02%		

Table A1.11: Cross-tabulation error matrix of classified RapidEye image versus reference data for 2013

Classified image	**Reference Data - 2011**			
	Forest &Woodland	*Unclassified*	*Oil palm*	*Row totals*
Forest & Woodland	0.368	0.028	0.016	0.413
Unclassified	0.013	0.541	0.001	0.557
Oil palm	0.005	0.001	0.004	0.030
Column totals	0.387	0.570	0.024	1
User's accuracy	89%	97%	80%	
Producer's accuracy	95%	95%	55%	
Total accuracy		93.28%		

Table A1.12: Land cover size of selected sites within the GGE for the years 2006, 2013, 2016, and 2021 from the Landsat dataset

Year	**Village land forest reserves**			**Unprotected village land**			**Gombe**		
	Forest cover Km^2	*Oil Palm* Km^2	*Unclassified land* Km^2	*Forest cover* Km^2	*Oil Palm* Km^2	*Unclassified land* Km^2	*Forest cover* Km^2	*Oil Palm* Km^2	*Unclassified land* Km^2
2006	21.05	0.78	71.54	14.78	7.35	39.05	26.66	0	8.99
2013	37.16	0.62	56.34	13.30	10.13	41.59	28.46	0	7.28
2016	34.61	0.61	57.90	11.59	10.40	43.00	28.45	0	7.35
2021	34.87	0.92	57.74	11.59	10.50	42.89	28.39	0	7.28

Table A1.13: DiD regression results show the coefficients and p-value of each variable we considered in the model.

	Dependent variable:
	Forest cover
Intercept	-0.251
	($p<0.001$)
Time	-0.054
	($p>0.05$)
Treatment	0.019
	($p>0.05$)
Time: Treatment	0.243
	($p<0.005$)

Table A1.14: Summary of model selection: Forest cover persistence in the VLFRs

Model	Intercept	Initial forest cover	Patrol	K	Δ_i	ω_i
Initial forest cover + Patrol	-0.052	0.01	0.04	4	0.00	0.98
Initial forest cover	-0.034	0.009		3	8.24	0.02
Patrol	0.1		0.14	3	53.54	0.00
Model-averaged parameter	-0.05	0.01	0.04			
2.5%	-0.08	0.01	0.02			
97.5%	-0.02	0.01	0.06			

Table A1.15: Summary of model selection: Forest cover gain in the VLFRs

Model	Intercept	Initial forest cover	Patrol	K	Δ_i	ω_i
Initial forest cover + Patrol	0.32	-0.01	0.1	4	0.00	0.87
Initial forest cover	0.36	-0.01		3	3.86	0.13
Patrol	0.19		0.01	3	16.48	0.00
Model-averaged parameter	45.95	-0.01	0.08			
2.5%	-189.05	-0.01	-0.01			
97.5%	280.96	0.00	0.17			

Table A1.16: Summary of model comparison: Forest gain.

Model	**K**	**Log Likelihood**	**Degree of Freedom**	**Chi square**	**P value**
Initial forest cover	3	12.31			
Initial forest cover + Patrol	4	16.06	1	7.50	0.006

Table A1.17: Summary of model comparison: Forest persistence.

Model	**K**	**Log Likelihood**	**Degree of Freedom**	**Chi square**	**P value**
Initial forest cover	3	28.88			
Initial forest cover + Patrol	4	34.82	1	11.87	0.0006

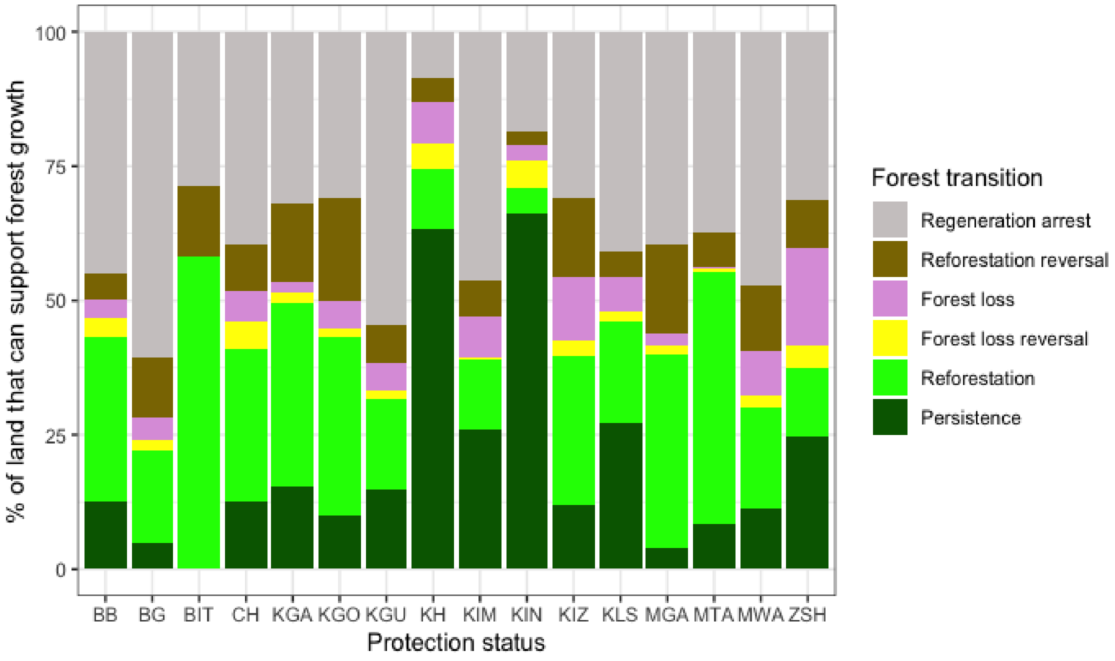

Figure A1.1. Aggregated land-cover trajectories over the study period for 16 VLFRs

KEY: BB=Bubango, BG=Bugamba, BIT=Bitale, CH=Chankele, KGA=Kagalye, KGO=Kagongo, KGU=Kagunga, KH=Kaharambuga, KIM=Kimanyama, KIN=Kinywe, KIZ=Kiziba, KLS=Kilasa, MGA=Mgaraganza, MTA=Mtanga, MWA=Mwamgongo, ZSH=Zashe

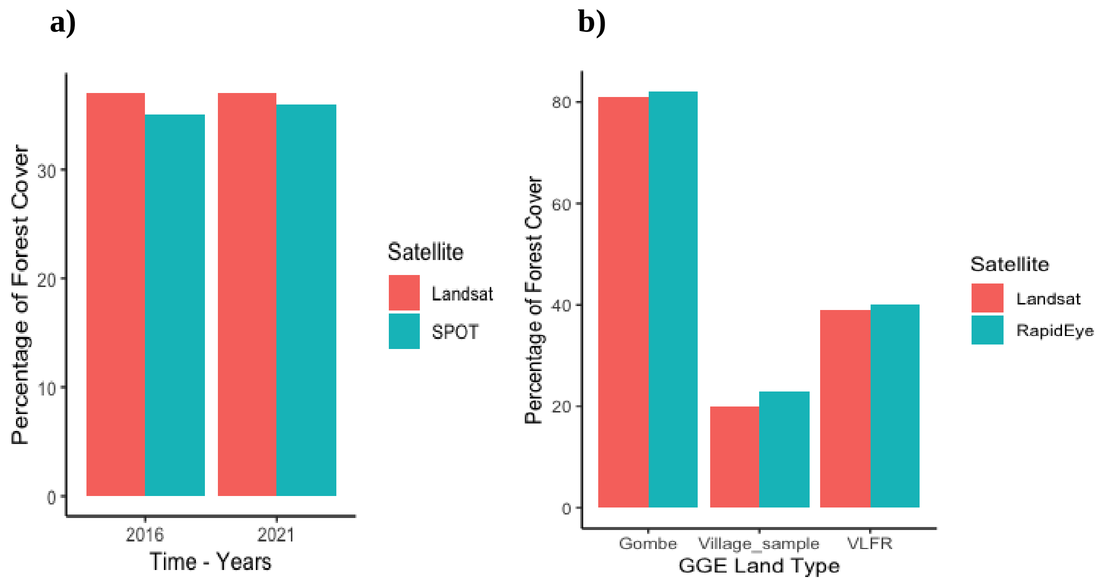

Figure A1.2: **A comparison of forest cover percentage between satellite images**, showing a minor difference in total forest cover estimates between Landsat and SPOT and Landsat and RapidEye satellites. (**a**) Landsat and SPOT images for 2016 and 2021 in the VLFRs, and (**b**) 2011 RapidEye and Landsat 2013

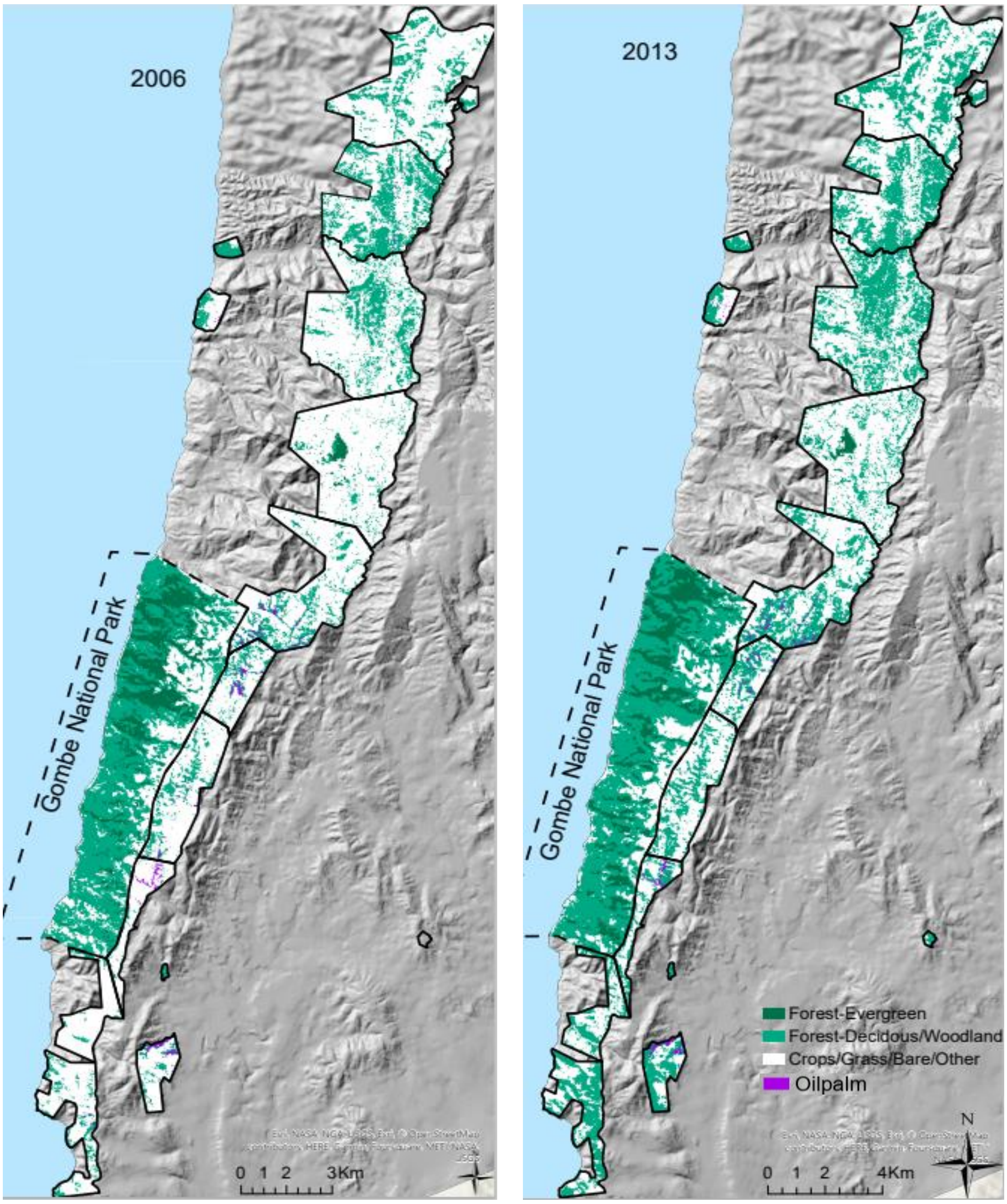

Fig A1.3: Classified maps showing land cover of 2006 and 2013 in VLFRs and Gombe NP from Landsat data.

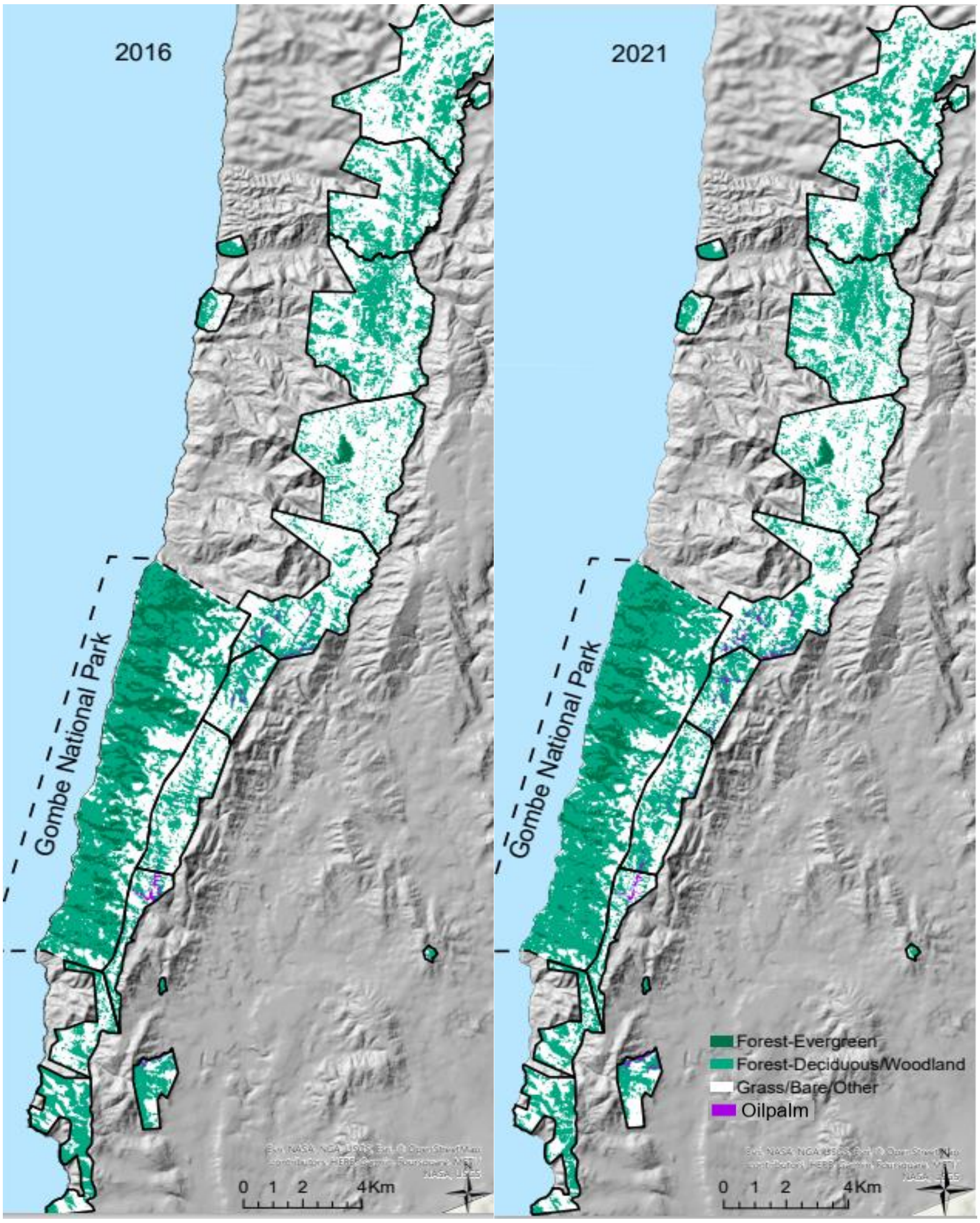

Fig A1.4: Classified maps showing land cover of 2016 and 2021 in VLFRs and Gombe NP from Landsat data.

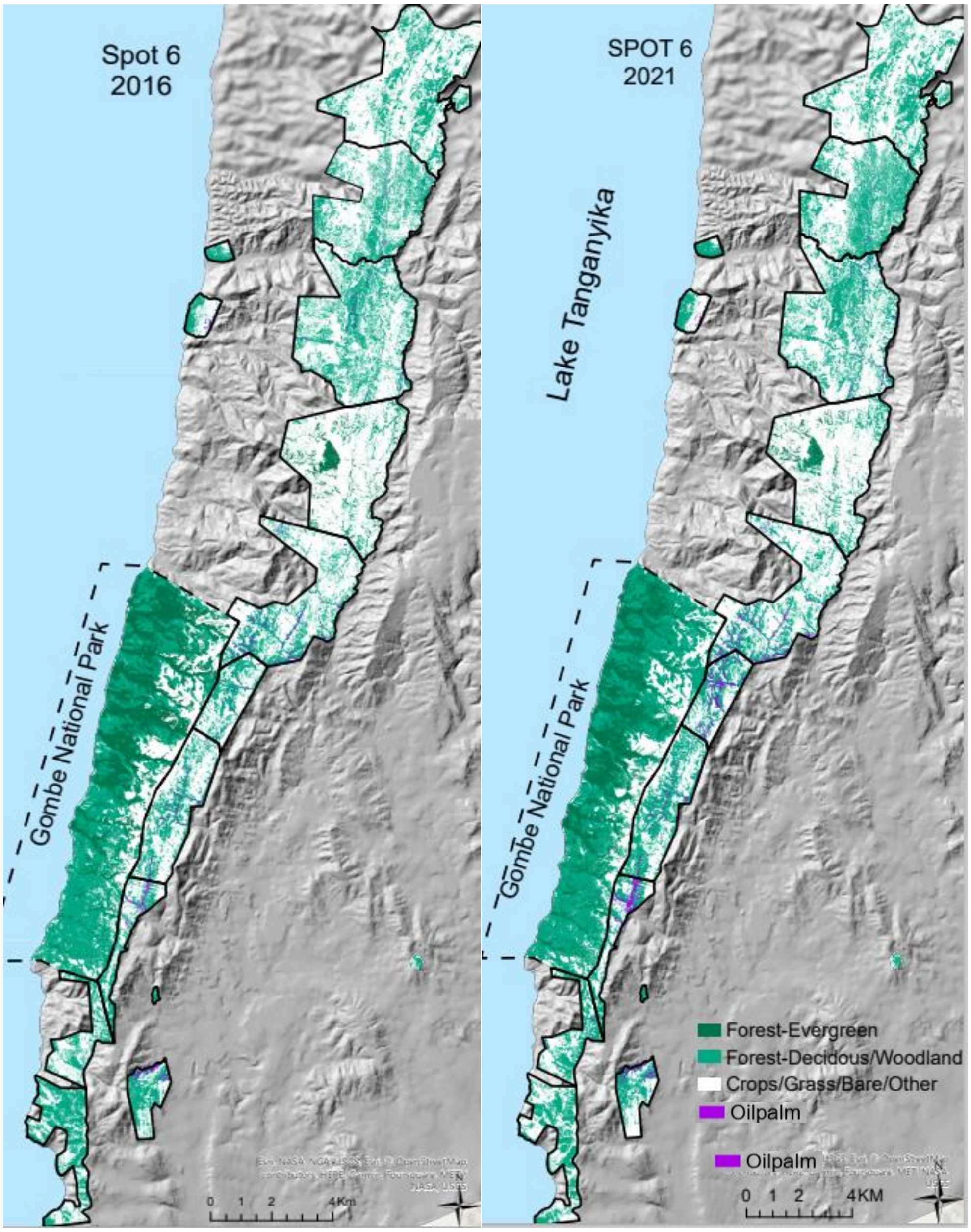

Fig A1.5: Classified maps showing land cover of 2016 and 2021 in VLFRs and Gombe NP from SPOT data.

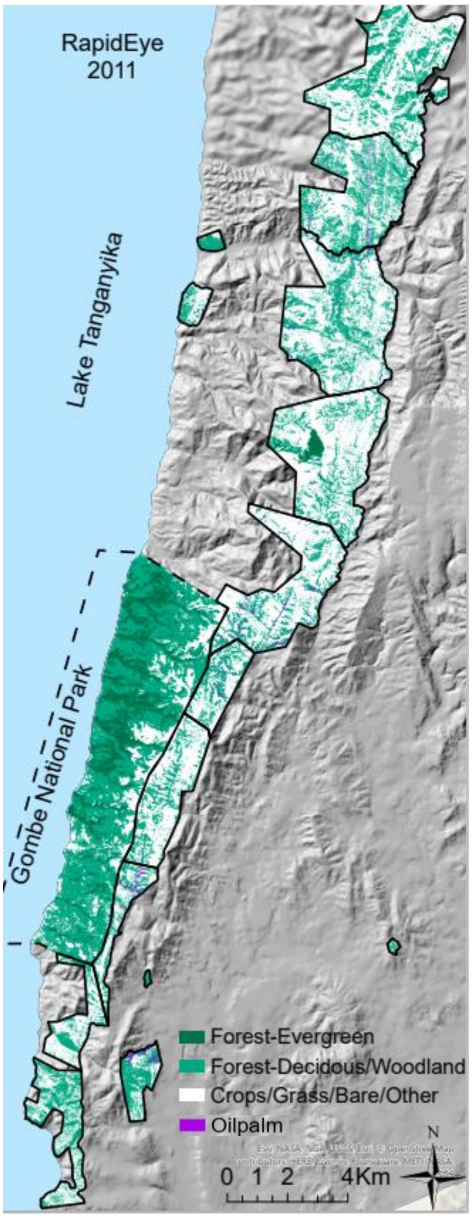

Fig A1.6: Classified map showing land cover of 2011 in VLFRs and Gombe NP from RapidEye data.

Reference Appendix I, Chapter 1

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Appendix for Chapter 2:

The relative influence of topographic and anthropogenic factors in forest cover change in the human modified landscape of the Greater Gombe Ecosystem, Tanzania

Table A2.1: Cross-tabulation error matrix of burnt area Landsat image versus reference data for 2020.

	Reference Data – 2020		
Classified image	*Burned*	*Unburned*	*Row totals*
Burned	0.363	0.009	0.372
Unburned	0.024	0.604	0.628
Column totals	0.387	0.613	1
User's accuracy	98%	96%	
Producer's accuracy	94%	98%	
Total accuracy		96.67%	

Table A2.2: Characteristics of images used in preparation of land cover maps and mask layer in the GGE (Chapter 1).

Imagery	**Acquisition Date**	**Spatial Resolution (m)**	**No. of Bands**	**Path/Row**	**Source**
Landsat 5	20 June 1984	30	7	172/63	USGS
Landsat 5	3 July 2006	30	7	172/63	USGS
Landsat 8	28 July 2021	30	11	172/63	USGS

Appendix for Chapter 3:

Community managed forests promote carbon sequestration, biodiversity, and quality habitat for primates in the human modified landscape of the Greater Gombe Ecosystem, Tanzania

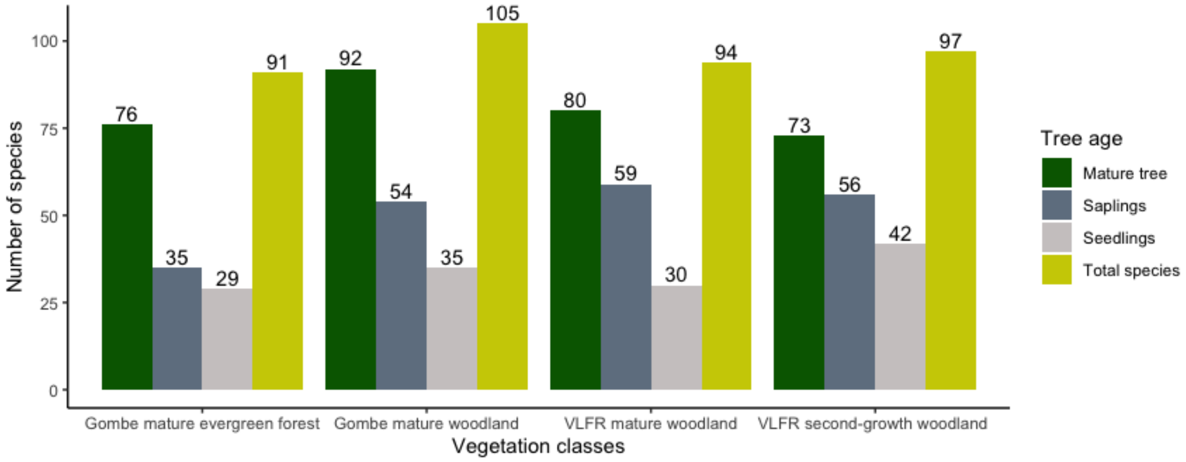

Figure A3.1: Observed species richness by tree age class in four vegetation classes in the GGE.

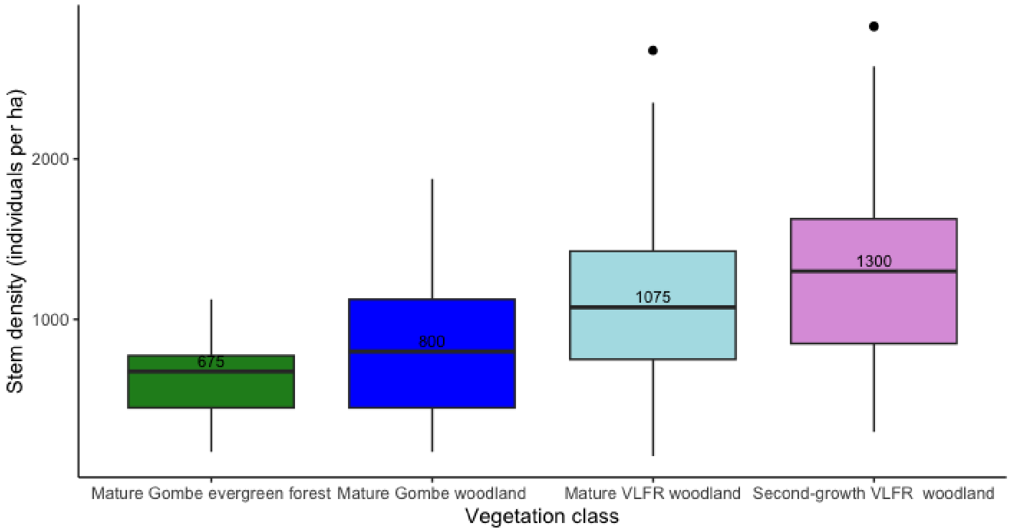

Figure A3.2: Boxplot showing the median density of stems with DBH> 5cm across vegetation classes. The interquartile range was 312, 675, 675, and 775 for the Gombe mature evergreen forest, Gombe mature woodland, VLFRs mature woodland, and VLFRs second-growth woodland, respectively.

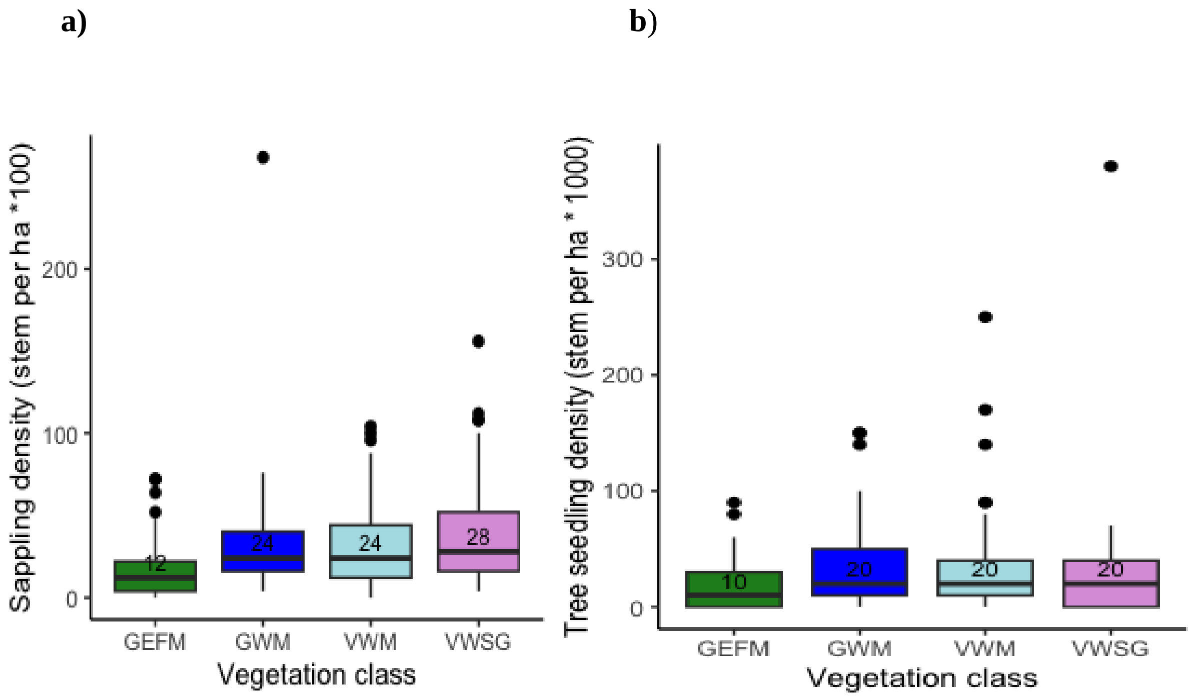

Figure A3.3: The variation of (a) sapling and (b) tree seedling density (stems/ha) across forest types (Gombe evergreen mature vs Gombe woodland mature), management strategy (Gombe woodland mature vs VLFR woodland mature) and forest age class (VLFR woodland mature vs VLFR woodland second-growth). The interquartile range for the a) sapling density was 18, 24, 32, and 36; and b) tree seedling density was 30, 40, 30, and 40 for the Gombe evergreen forest mature, Gombe woodland mature, VLFRs woodland mature, and VLFRs woodland second-growth.

Key: GEFM = Gombe mature evergreen forest, GWM= Gombe mature woodland, VWM= VLFR mature woodland, VWSG=VLFR second-growth woodland

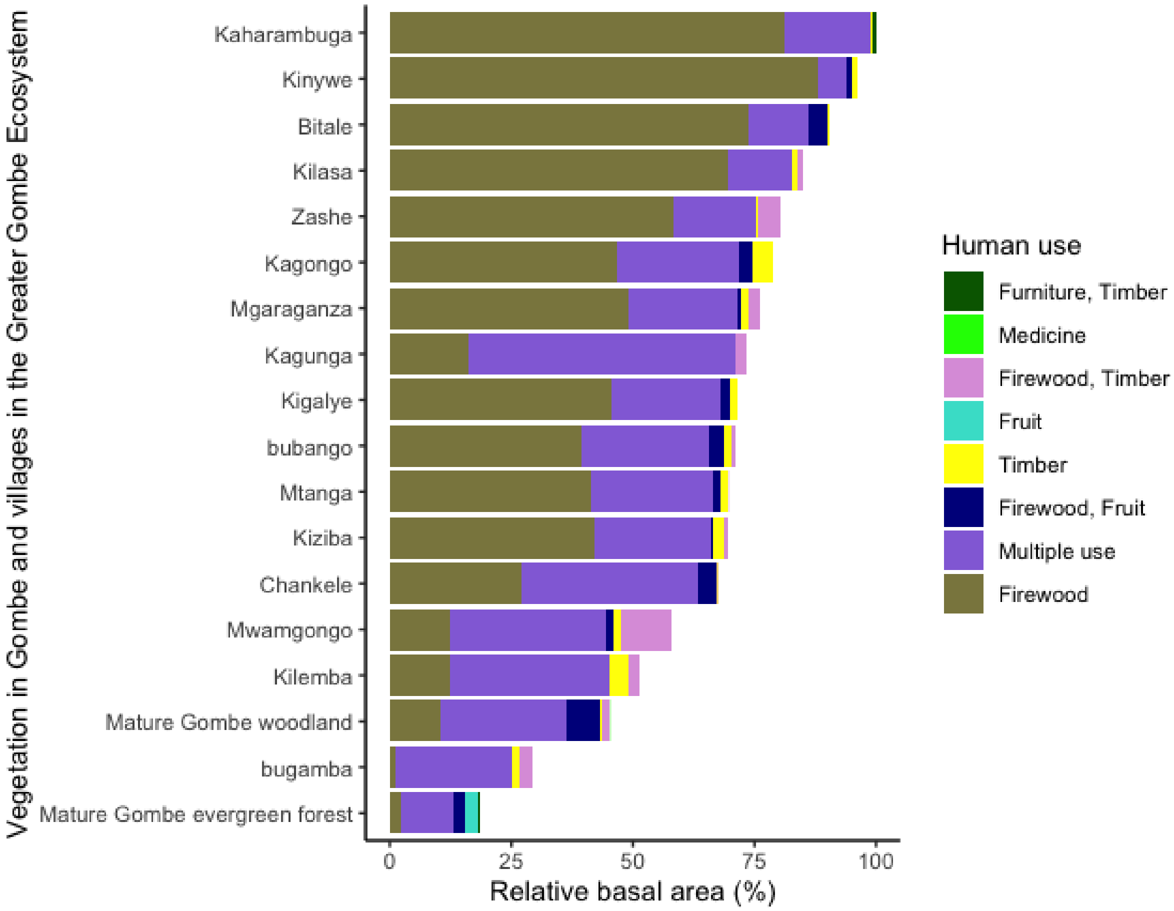

Figure A3.4: Relative basal area of tree species perceived as important by local people per VLFRs and Gombe mature evergreen forest and woodland.

Table A3.1: Likelihood ratio test of the linear mixed model of the effect of forest age on forest attributes in the VLFRs

Response variable	Explanatory variable	Estimate	Standard error	Degrees of freedom	t value	p value
Basal area	Intercept	8.36	0.59	28.14	14.14	0.0001
	Forest age	3.98	0.63	164.15	6.32	0.0001
Stem density	Intercept	1199	91.32	16.51	13.13	0.0001
	Forest age	-63.41	84.89	171.95	-0.75	>0.05
General habitat quality	Intercept	7.54	0.61	26.74	12.36	0.0001
	Forest age	3.48	0.67	159.62	5.19	0.0001
Preferred-tree habitat quality	Intercept	2.45	0.59	21.74	4.15	0.0001
	Forest age	1.45	0.48	175.00	3.04	0.003
Carbon stock	Intercept	20.02	2.27	27.78	8.84	0.0001
	Forest age	13.82	2.34	168.28	5.906	0.0001

Table A3.2: T-test results for forest management and forest type questions

Hypothesis	Vegetation classes	Response variables	T-statistics	Degrees of freedom	P-value
Forest management question	Mature woodland of Gombe NP **vs** mature woodland of VLFR	Basal area	3.57	61.72	0.0001
		Stem density	-3.522	109.93	0.0001
		Carbon stock	4.78	62.04	0.0001
		General HBQ	3.03	64.59	0.001
		High-tree HBQ	2.34	75.53	0.01
		Value to local people	0	14	*>0.05*
Forest type question	Mature evergreen forest **vs** mature woodland of Gombe NP	Basal area	0.75	66.77	*> 0.05*
		Stem density	-2.57	77.73	0.01
		Carbon stock	1.42	57.48	*>0.05*
		General HBQ	1.32	70.16	>0.05
		High-tree HBQ	0.89	56.82	*>0.05*
		Value to local people	2.25	7.73	*<0.05*

Key: HBQ = Habitat quality

Table A3.3: Amount of tree carbon stock sequestered at Gombe and Village Land Forest Reserves

Vegetation Class	Forest Cover in Ha	Carbon Stock in Mg
Gombe – Evergreen	499.23	34496.79
Gombe – Woodland	2346.3	134443.00
VLFR – Mature	1426.23	48520.34
VLFR – Second growth	2061.45	37229.79

Table A3.4: Estimated tree above-ground carbon stock in megagrams per hectare (mean and 95% Confidence Intervals) for different vegetation classes, using pan-tropical model from Chave et al., (2015).

Vegetation Class	Year	Aboveground Carbon Mg C ha^{-1}	95% Confidence Interval
Evergreen Forest – Gombe	2021	59.31	53.26 – 66.64
Woodland – Gombe	2021	57.90	52.26 – 63.52
Mature Forest – VLFR	2021	34.31	31.22 – 37.75
Second-growth - VLFR	2021	18.18	16.47 – 19.90

Table A3.5: The estimated tree above-ground carbon stock in megagrams per hectare (mean and 95% Confidence Intervals) for different vegetation classes using model that uses *dbh* Mugasha et al., (2013).

Vegetation Class	Year	Aboveground Carbon Mg C ha^{-1}	95% Confidence Interval
Evergreen Forest – Gombe	2021	59.65	54.17 – 64.75
Woodland – Gombe	2021	48.21	43.35 – 53.09
Mature Forest – VLFR	2021	28.52	25.88 – 31.49
Second-growth - VLFR	2021	15.23	13.79 – 16.67

Table A3.6: Number of tree species composition in each vegetation class.

S/No	Species	Gombe evergreen mature	Gombe woodland mature	VLFRs woodland mature	VLFRs woodland secondary
1	*Afzelia quanzensis*			5	1
2	*Albizia adianthifolia*			7	
3	*Albizia antunesiana*		15	63	53
4	*Albizia glaberrima*	6	4	7	5
5	*Albizia versicolor*				1
6	*Allophylus congolanus*	1	7		
7	*Anisophyllea boehmii*	26	45	138	245
8	*Annona senegalensis*	28	197	11	13
9	*Anthocleista grandiflora*	33	22		
10	*Anthocleista schweinfurthii*	23	4	3	
11	*Antiaris toxicaria*	7			
12	*Antidesma venosum*	21	64	2	2
13	*Azanza garckeana*	3	8		
14	*Bauhinia petersiana*				1
15	*Blighia unijugata*	15	2		
16	*Boscia salicifolia*			2	
17	*Brachystegia boehmii*		1	417	85
18	*Brachystegia bussei*	3	33	973	1221
19	*Brachystegia longifolia*			8	5
20	*Brachystegia microphylla*	6	20	118	253
21	*Brachystegia spiciformis*			28	78
22	*Brachystegia utilis*	1		59	35
23	*Bridelia atroviridis*	20	29	6	2
24	*Bridelia cathartica*	2	33		
25	*Bridelia micrantha*	1			
26	*Burkea africana*			11	2
27	*Canthium lactescens*			7	
28	*Canthium oligocarpum*		1	2	1
29	*Carpolobia conradsiana*	2			
30	*Cassia singueana*		1	1	
31	*Celtis africana*	4			
32	*Combretum collinum*	9	10	16	2
33	*Combretum molle*	64	86	51	40
34	*Combretum psidioides*		1	1	
35	*Commiphora pteleifolia*	4	16		
36	*Craibia brevicaudata*	4			

37	*Crossopteryx febrifuga*		19	8	6
38	*Croton sylvaticus*	56	40		
39	*Cussonia arborea*		5	12	4
40	*Dalbergia nitidula*		2	68	56
41	*Dichrostachys cinerea*			2	
42	*Dichapetalum stuhlmannii*		1		
43	*Diplorhynchus condylocarpon*	13	234	231	241
44	*Dracaena usambarensis*	1	7		
45	*Drypetes gerrardii*		1		
46	*Ekebergia capensis*	86	12	41	
47	*Elaeis guineensis*	7			
48	*Englerophytum natalense*			4	
49	*Erica arborea*			2	
50	*Erythrina excelsa*				2
51	*Faurea saligna*	10	21	71	13
52	*Ficus ottoniifolia*	2	1		
53	*Ficus exasperata*			1	
54	*Ficus sansibarica*	1			
55	*Ficus spp*		1		
56	*Ficus sycomorus*		4		2
57	*Ficus trichopoda*		1		4
58	*Ficus vallis-choudae*	2			
59	*Flacourtia indica*	3	1		
60	*Garcinia buchananii*				1
61	*Garcinia huillensis*	2	15	6	2
62	*Garcinia volkensii*			1	
63	*Grewia mollis*	1	18		
64	*Haplocoelum inoploeum*	2			
65	*Harrisonia abyssinica*	3	29		
66	*Harungana madagascariensis*		1	1	
67	*Holarrhena febrifuga*		12		5
68	*Hymenocardia acida*		41	16	4
69	*Isoberlinia angolensis*			1	23
70	*Julbernardia globliflora*	4	7	266	340
71	*Kigelia africana*	7			
72	*Lannea schimperi*	3	21	14	12
73	*Lecaniodiscus fraxinifolius*		1		2
74	*Mangifera indica*				3
75	*Maesopsis eminii*	2	4		
76	*Maprounea africana*		1	26	25
77	*Margaritaria discoidea*	7	9	23	

78	*Markhamia obtusfolia*	3	15	3	1
79	*Memecylon flavovirens*			1	2
80	*Merremia pterylocaulos*				2
81	*Milicia excelsa*	1	1		
82	*Monotes elegans*		21	61	43
83	*Multidentia crassa*	1	8	6	12
84	*Myrianthus arboreus*	7			
85	*Newtonia buchananii*	45	3		
86	*Nuxia congesta*	14	10		
87	*Ochna holstii*		3	10	3
88	*Ochna schweinfurthiana*	4	6	21	4
89	*Oxyanthus speciosus*	34	19		
90	*Parinari curatellifolia*	12	45	99	132
91	*Pavetta schumanniana*		9	4	3
92	*Pericopsis angolensis*		10	40	18
93	*Phyllanthus muellerianus*	2			2
94	*Piliostigma thonningii*		1		
95	*Premna angolensis*		3		
96	*Protea gaguedi*			23	2
97	*Protea petiolaris*			29	7
98	*Protea suffruticosa*			9	
99	*Pseudolachnostylis maprouneifolia*	1		5	18
100	*Pseudospondias microcarpa*	33	2		
101	*Psorospermum febrifugum*		2	14	20
102	*Pterocarpus angolensis*	4	17	102	114
103	*Pterocarpus tinctorius*	7	10	84	89
104	*Pycnanthus angolensis*	4			
105	*Rhus natalensis*		3		
106	*Rothmannia engleriana*	4	11	57	40
107	*Scherebella trichoclada*		9	4	5
108	*Schrebera alata*	14	25		
109	*Securidaca longipedunculata*			6	
110	*Sorindeia madagascariensis*	26	1	3	
111	*Spathodea campanulata*		1		
112	*Steganotaenia araliacea*			1	2
113	*Sterculia africana*		3	4	2
114	*Sterculia tragacantha*	7	31		
115	*Stereospermum kunthahinum*	4	59	4	2
116	*Strychnos cocculoides*	1		14	9
117	*Strychnos madagascariensis*		6	25	18
118	*Strychnos potatorum*	5	21	2	

119	*Synsepalum brevipes*	13			
120	*Syzygium cuminii*		21	7	3
121	*Syzygium guineense*	9	10		3
122	*Tabernaemontana holstii*	29		4	
123	*Tarenna pavettoides*	2			
124	*Terminalia kaiserana*	2	21		2
125	*Terminalia mollis*	1	19	4	4
126	*Trema orientalis*	1	2	9	
127	*Tricalysia verdcourtiana*	1			
128	*Uapaca kirkiana*	14	6	639	214
129	*Uapaca nitida*	20	55	411	250
130	*Uapaca sansibarica*		1	128	22
131	*Uvariodendron gorgonis*	6	4		
132	*Vachellia polycantha*				3
133	*Vachellia hockii*		2		
134	*Vangueria madagascariensis*	2	7		
135	*Vernonia colorata*		6		
136	*Vitex doniana*	2	4	3	18
137	*Vitex fischeri*	30	8	4	4
138	*Vitex mombassae*		4	10	3
139	*Ximenia americana*			7	3
140	*Zanha africana*				8

Table A3.7: The number of tree saplings for each vegetation classes.

S/No	Species	Gombe evergreen mature	Gombe woodland mature	VLFRs woodland mature	VLFRs woodland secondary
1	*Albizia adianthifolia*		1	1	2
2	*Albizia antunesiana*		1	11	7
3	*Albizia glaberrima*	1	3	8	
4	*Allophylus congolanus*	1	11		
5	*Anisophyllea boehmii*	3	2	14	16
6	*Annona senegalensis*		8	2	4
7	*Anthocleista grandiflora*	3	3		1
8	*Anthocleista schweinfurthii*		2	2	
9	*Antidesma venosum*	1	6	7	2
10	*Baphia massaiensis*			1	
11	*Blighia unijugata*	1	1		
12	*Brachystegia boehmii*			4	2
13	*Brachystegia bussei*		1	23	35
14	*Brachystegia longifolia*			1	1
15	*Brachystegia microphylla*		1	10	11
16	*Brachystegia spiciformis*			3	5
17	*Brachystegia utilis*	1			1
18	*Bridelia atroviridis*	1	4	1	
19	*Burkea africana*			1	
20	*Chionanthus niloticus*				1
21	*Canthium oligocarpum*			7	
22	*Combretum collinum*				2
23	*Combretum molle*	4	13	11	2
24	*Commiphora pteleifolia*		2		
25	*Crossopteryx febrifuga*		2	1	
26	*Croton sylvaticus*		5		
27	*Cussonia arborea*			1	
28	*Dalbergia lactea*				1
29	*Dalbergia nitidula*		1	16	6
30	*Dalbergia malangensis*		1		
31	*Dichrostachys cinerea*				1
32	*Dichapetalum stuhlmannii*		1		
33	*Diplorhynchus condylocarpon*		11	12	17
34	*Drypetes gerrardii*		1		
35	*Erica arborea*			1	

36	*Faurea saligna*	1	2	14	3
37	*Ficus attonifolia*	1			
38	*Ficus vallis-choudae*	1			
39	*Garcinia buchananii*			1	1
40	*Garcinia huillensis*	3	9	8	1
41	*Harrisonia abyssinica*		1		
42	*Harungana madagascariensis*	1	4	1	2
43	*Holarrhena febrifuga*		1		1
44	*Hymenocardia acida*		1	4	2
45	*Isoberlinia angolensis*				2
46	*Julbernardia globliflora*		1	13	10
47	*Kigelia africana*	4			
48	*Lannea schimperi*				3
49	*Lecaniodiscus fraxinifolius*		1		
50	*Maprounea africana*				7
51	*Margaritaria discoidea*		5	5	14
52	*Markhamia obtusfolia*	1	2	2	1
53	*Monotes elegans*			3	
54	*Multidentia crassa*		6	8	7
55	*Myrianthus arboreus*	1			
56	*Newtonia buchananii*	2			
57	*Ochna holstii*			5	1
58	*Ochna schweinfurthiana*	2	5	7	10
59	*Oxyanthus speciosus*	2	2		
60	*Pancovia turbinata*	8	1	4	
61	*Parinari curatellifolia*	2	1	11	15
62	*Pavetta schumanniana*		2	3	1
63	*Pericopsis angolensis*			3	2
64	*Phyllanthus muellerianus*			1	1
65	*Protea gaguedi*			1	1
66	*Pseudolachnostylis maprouneifolia*		2	1	3
67	*Psorospermum febrifugum*		1	8	14
68	*Pterocarpus angolensis*		2	4	7
69	*Pterocarpus tinctorius*		1	3	9
70	*Pycnanthus angolensis*	1			
71	*Rothmannia engleriana*	2	7	14	13
72	*Scherebella trichoclada*		1	1	3
73	*Schrebera alata*		2		
74	*Securidaca longipedunculata*		8		
75	*Sorindeia madagascariensis*	1		1	
76	*Spathodea campanulata*			2	

77	*Sterculia africana*				1
78	*Sterculia tragacantha*	3		1	
79	*Stereospermum kunthahinum*	1	11	1	2
80	*Strychnos cocculoides*	1	1	11	3
81	*Strychnos madagascariensis*	2	3	7	3
82	*Strychnos pungens*				1
83	*Syzygium guineense*	1	3	1	
84	*Tabernaemontana holstii*	4			
85	*Terminalia mollis*				1
86	*Uapaca kirkiana*			19	7
87	*Uapaca nitida*			13	9
88	*Uapaca sansibarica*	2	2		2
89	*Vangueria madagascariensis*	1			
90	*Vitex doniana*	1	1	2	
91	*Vitex fischeri*	1	1		
92	*Vitex mombassae*			4	3
93	*Ximenia americana*		1	2	1

Table A3.8: Number of tree seedlings for each vegetation class.

S/No	Species	Gombe evergreen mature	Gombe woodland mature	VLFRs woodland mature	VLFRs woodland secondary
1	*Albizia adianthifolia*	1		3	
2	*Albizia antunesiana*		1	5	3
3	*Albizia glaberrima*	2		5	
4	*Allophylus congolanus*		9		
5	*Anisophyllea boehmii*	1		4	4
6	*Annona senegalensis*		3		
7	*Anthocleista grandiflora*	3	3		
8	*Anthocleista schweinfurthii*	1	2		
9	*Antidesma venosum*	1	2	4	
10	*Antiaris toxicaria*	1			
11	*Brachystegia boehmii*			3	1
12	*Brachystegia bussei*		4	19	18
13	*Brachystegia longifolia*			1	1
14	*Brachystegia microphylla*	1		8	2
15	*Brachystegia spiciformis*			1	1
16	*Brachystegia utilis*			2	
17	*Bridelia atroviridis*	1	4		1
18	*Burkea africana*			1	
19	*Canthium lactescens*			1	
20	*Canthium oligocarpum*			1	
21	*Combretum molle*	1	2	1	1
22	*Commiphora pteleifolia*		3		
23	*Dalbergia nitidula*		1	1	1
24	*Diplorhynchus condylocarpon*		4	6	13
25	*Elaeis guineensis*	1			
26	*Faurea saligna*	1	1	4	1
27	*Flacourtia indica*	1			
28	*Garcinia huillensis*	7	9	1	2
29	*Harrisonia abyssinica*		2		
30	*Harungana madagascariensis*	1			
31	*Hymenocardia acida*			1	
32	*Julbernardia globliflora*			8	8
33	*Lannea schimperi*		2		
34	*Maprounea africana*				1

35	*Margaritaria discoidea*		4	1	5
36	*Markhamia obtusfolia*		1	1	
37	*Multidentia crassa*			1	
38	*Newtonia buchananii*	4	1		
39	*Ochna holstii*			2	1
40	*Ochna schweinfurthiana*	2	2	6	3
41	*Oxyanthus speciosus*	1			
42	*Pancovia turbinata*	2		3	1
43	*Parinari curatellifolia*			3	5
44	*Pericopsis angolensis*			1	
45	*Protea gaguedi*			1	
46	*Protea petiolaris*				1
47	*Pseudolachnostylis maprouneifolia*				1
48	*Psorospermum febrifugum*	1		2	3
49	*Pterocarpus angolensis*			1	1
50	*Pterocarpus tinctorius*			2	
51	*Rothmannia engleriana*		8	4	2
52	*Scherebella trichoclada*		2		
53	*Sorindeia madagascariensis*	2			
54	*Sterculia tragacantha*	1	6		
55	*Stereospermum kunthahinum*		4		
56	*Strychnos cocculoides*		1	4	
57	*Strychnos madagascariensis*	2	2	4	2
58	*Syzygium guineense*		1	1	1
59	*Tabernaemontana holstii*	1			
60	*Tarenna pavettoides*		2		
61	*Tricalysia verdcourtiana*			1	1
62	*Uapaca kirkiana*			7	
63	*Uapaca nitida*			14	5
64	*Uapaca sansibarica*	1	2	2	1
65	*Vangueria madagascariensis*	1			
66	*Vitex doniana*		1		
67	*Vitex fischeri*	1	4		
68	*Ximenia americana*			2	

Table A3.9: Chimpanzee plant food species in the Greater Gombe Ecosystem.

S/No	Species	Confirmed Plant Food - Gombe National Park	Confirmed plant food – other chimpanzee sites in western Tanzania*
1	*Afzelia quanzensis*	x	x
2	*Albizia adianthifolia*	x	x
3	*Albizia antunesiana*	x	x
4	*Albizia glaberrima*	x	x
5	*Anisophyllea boehmii*	x	x
6	*Annona senegalensis*	x	x
7	*Anthocleista grandiflora*	x	x
8	*Anthocleista schweinfurthii*	x	x
9	*Antiaris toxicaria*	x	x
10	*Antidesma venosum*	x	x
11	*Azanza garckeana*	x	x
12	*Baphia massaiensis*	x	x
13	*Blighia unijugata*		x
14	*Brachystegia boehmii*		x
15	*Brachystegia bussei*	x	x
16	*Brachystegia longifolia*		x
17	*Brachystegia spiciformis*		x
18	*Bridelia atroviridis*	x	x
19	*Bridelia cathartica*	x	x
20	*Bridelia micrantha*	x	x
21	*Celtis africana*	x	x
22	*Combretum molle*	x	x
23	*Croton sylvaticus*	x	x
24	*Cussonia arborea*	x	x
25	*Dalbergia nitidula*		x
26	*Dichapetalum stuhlmannii*		x
27	*Diplorhynchus condylocarpon*	x	x
28	*Dombeya rotundifolia*		x
29	*Elaeis guineensis*	x	x
30	*Ficus asperifolia*	x	x
31	*Ficus attonifolia*	x	x
32	*Ficus exasperata*	x	x
33	*Ficus sansibarica*	x	x
34	*Ficus sycomorus*	x	x

35	*Ficus trichopoda*	x	x
36	*Ficus vallis-choudae*	x	x
37	*Flacourtia indica*	x	x
38	*Garcinia buchananii*	x	x
39	*Garcinia huillensis*	x	x
40	*Grewia mollis*	x	x
41	*Grewia platyclada*		x
42	*Harrisonia abyssinica*	x	x
43	*Harungana madagascariensis*	x	x
44	*Holarrhena febrifuga*	x	x
45	*Hymenocardia acida*	x	x
46	*Isoberlinia angolensis*	x	x
47	*Julbernardia globliflora*	x	x
48	*Lannea schimperi*		x
49	*Maesopsis eminii*	x	x
50	*Mangifera indica*	x	x
51	*Maprounea africana*	x	x
52	*Margaritaria discoidea*		x
53	*Markhamia obtusfolia*		x
54	*Milicia excelsa*	x	x
55	*Monotes elegans*		x
56	*Multidentia crassa*	x	x
57	*Myrianthus arboreus*	x	x
58	*Newtonia buchananii*	x	x
59	*Nuxia congesta*	x	x
60	*Oxyanthus speciosus*	x	x
61	*Pancovia turbinata*	x	x
62	*Parinari curatellifolia*	x	x
63	*Pericopsis angolensis*	x	x
64	*Phyllanthus muellerianus*	x	x
65	*Piliostigma thonningii*	x	x
66	*Pseudolachnostylis maprouneifolia*		x
67	*Pseudospondias microcarpa*	x	x
68	*Pterocarpus angolensis*	x	x
69	*Pterocarpus tinctorius*	x	x
70	*Pycnanthus angolensis*	x	x
71	*Rhus anchietae*	x	x
72	*Rhus natalensis*	x	x
73	*Rothmannia engleriana*	x	x
74	*Scherebella trichoclada*		x
75	*Schrebera alata*		x

76	*Sorindeia madagascariensis*	x	x
77	*Sterculia africana*	x	x
78	*Sterculia tragacantha*	x	x
79	*Stereospermum kunthahinum*		x
80	*Strychnos cocculoides*	x	x
81	*Strychnos madagascariensis*	x	x
82	*Strychnos pungens*	x	x
83	*Synsepalum brevipes*	x	x
84	*Syzygium cuminii*	x	x
85	*Syzygium guineense*	x	x
86	*Tabernaemontana holstii*	x	x
87	*Tarenna pavettoides*	x	x
88	*Terminalia mollis*		x
89	*Trichilia emetica*	x	x
90	*Uapaca kirkiana*	x	x
91	*Uapaca nitida*	x	x
92	*Uapaca sansibarica*	x	x
93	*Uvariodendron gorgonis*	x	x
94	*Vachellia hockii*	x	x
95	*Vachellia polyacantha*		x
96	*Vitex doniana*	x	x
97	*Vitex fischeri*	x	x
98	*Vitex mombassae*		x
99	*Ximenia americana*	x	x
100	*Zanha africana*		x
101	*Zanha golungensis*		x

Key:

***** Nishida and Uehara (1983); Yoshikawa and Ogawa (2015); and Piel et al., (2017)

Reference for Appendix for Chapter 3

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