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Using Repeat Photography to Observe Vegetation Change Over Time in Gorongosa National Park

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Abstract: Protected areas are important conservation tools, as they can be managed to preserve baseline ecosystem health, including that of vegetation dynamics. Understanding long-term ecosystem dynamics within a protected area enables one to understand how this static park landscape responds to outside pressure and changing drivers. In this study, a repeat photography analysis was used to analyze changes in the vegetation pattern and abundance at Gorongosa National Park in Mozambique across seventy-two years of the parks history. Archival photographs dating as far back as 1940 were selected for sites that could be relocated in a subsequent field visit in 2012. Qualitative and quantitative analysis on vegetation abundance by structural group was undertaken using Edwards' Tabular Key. Results when comparing the photographic pairs show that, in general, tree cover has increased on average from 25 percent to 40 percent over the last seventy-two years. This 15 percent increase may be in response to environmental drivers such as human management, herbivory, fire, and precipitation. Contrary to many recent studies on shrub encroachment in southern Africa, this study finds an increase in tree cover. Such analysis and results are valuable in that they demonstrate long-term ecological change within a managed protected area.

Introduction

Dryland ecosystems, defined as water limited systems, cover more land globally than any other ecosystem type and range from desert to savanna landscapes in their structure. Globally, dryland ecosystems are projected to experience broad scale change in composition and

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productivity related to global environmental change, specifically climate change. Dryland expansion has been noted globally and caused by a net reduction in soil available moisture due to changes in precipitation regimes. This global expansion of drylands has resulted in savanna like composition in new and ever expanding areas.[1] Savannas, such as those that dominate Gorongosa National Park (GNP) sustain up to one-third of the world's human population and 13.6 percent of global Net Primary Productivity.[2] Savannas are a globally distributed ecosystem that can be defined as grassland with scattered trees or shrubs. Across southern Africa upwards of 54 percent of the landscape is deemed savanna and these areas are highly heterogeneous in composition.[3] The primary drivers of savanna pattern and process that produce differential responses of vegetation cover are fire, grazing, climate variability and agriculture.[4]

Monitoring land-cover changes in savanna ecosystems can be difficult because of their highly heterogeneous composition.[5] However, monitoring these system changes is important to ecosystem function and diversity. Therefore, it is critical to monitor land-cover changes across these sensitive savanna regions as events such as shrub encroachment and landscape degradation have been noted in the literature.[6] Up to 31 percent of southern Africa's savannas may be considered degraded.[7] Landscape degradation in this context is defined as a decrease in vegetation cover (or even a complete loss), a shift in species towards annual plants, shrub encroachment (vegetation densification), long-term overgrazing, weakening perennial grasses, and/or a decrease in biodiversity.[8] Shrub encroachment is an ecological process observed across Southern Africa, including South Africa and Botswana.[9] However, a literature review shows that across Mozambique, particularly in and around GNP, studies on and quantification of shrub encroachment have not taken place. The present study aims to remedy this. Shrub encroachment is of particular concern to ecologists because of the transformation of habitats, that is to say, the loss of one habitat and the gain of a fundamentally different, and often less desirable, type.[10] Potential impacts of shrub encroachment are biogeochemical and biophysical changes. Factors that catalyze shrub encroachment are the exclusive use of moisture by the encroaching shrub species, high amounts of soil nutrients, low fire frequency, and high cattle selectivity.[11]

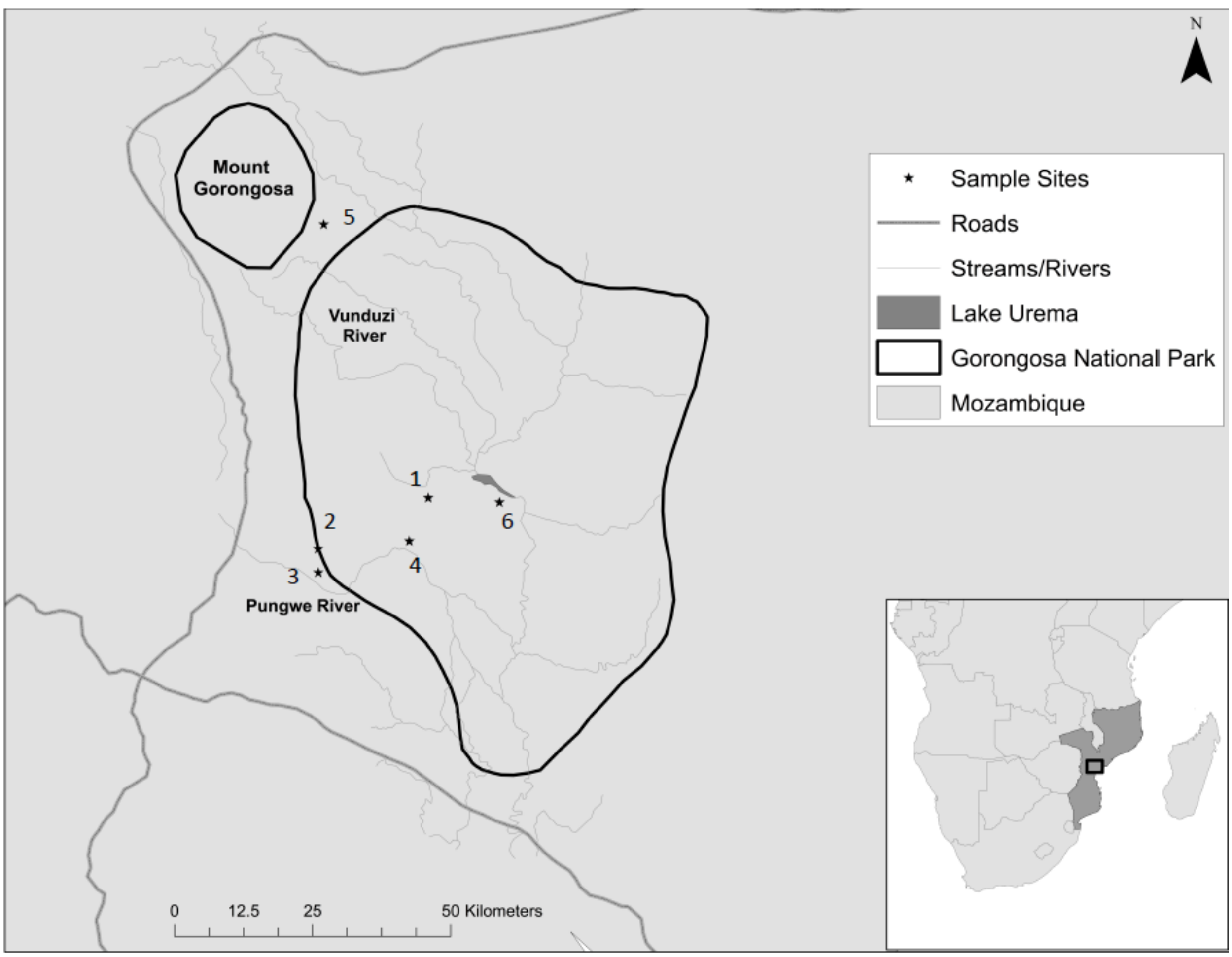
Remote measurements of past landscapes can be used to study change over time. One way this can be done is via the use of traditional photography, specifically a process called repeat photography. Repeat photography is the practice of taking a photograph from the same physical perspective at different points in time. This is a technique that was first developed in Europe in the 1880s to evaluate landscape change with glaciers.[12] It has since expanded across all ecosystems types globally.[13] Repeat photography is a valuable tool because it gives us a much longer time-series of data than satellite remote sensing alone, which only goes back to the mid-1970s, and in terms of more useful spatial and temporal analysis, the mid-1980s. We also have a much higher spatial resolution with ground-point photography.[14]

Gorongosa National Park (GNP), where this research was undertaken, is a mid-latitude highly heterogeneous savanna landscape, which has undergone significant human influence across the last 70 years. [15] The goal of this study is to assess vegetation change, in particular related to tree and shrub covers using repeat photography with two related research questions. This research therefore asks: (1) has there been a change in tree cover? (2) has there been a change in shrub cover to indicate any potential shrub encroachment as has happened across many other savanna park landscapes?

Study Area

Gorongosa National Park, whose area is around 4000 km², is located at approximately 18.2°S and 34.0°E (Figure 1). The average temperature in the park fluctuates between 15°C and 30°C with mean annual precipitation (MAP) from 1981 to 2016 of ~1000 mm (Figure 2), but it has slightly decreased over time. The minimum total annual precipitation was ~650 mm in 1992 and the maximum total annual precipitation was ~1625 mm in 2001. In GNP, the wet season lasts from November to March, which is driven by the migration of the Intertropical Convergence Zone. The park is located south of the Zambezi River, north of the Pungwe River, west of the Indian Ocean, and east of Mount Gorongosa. The elevation of the park ranges from around fifteen meters in the lowlands to 1800 meters on the mountaintop. The Gorongosa ecosystem is very complex and contains multiple types of habitats including savanna, miombo, and montane forest, but the main focus of this project is on the savannas.

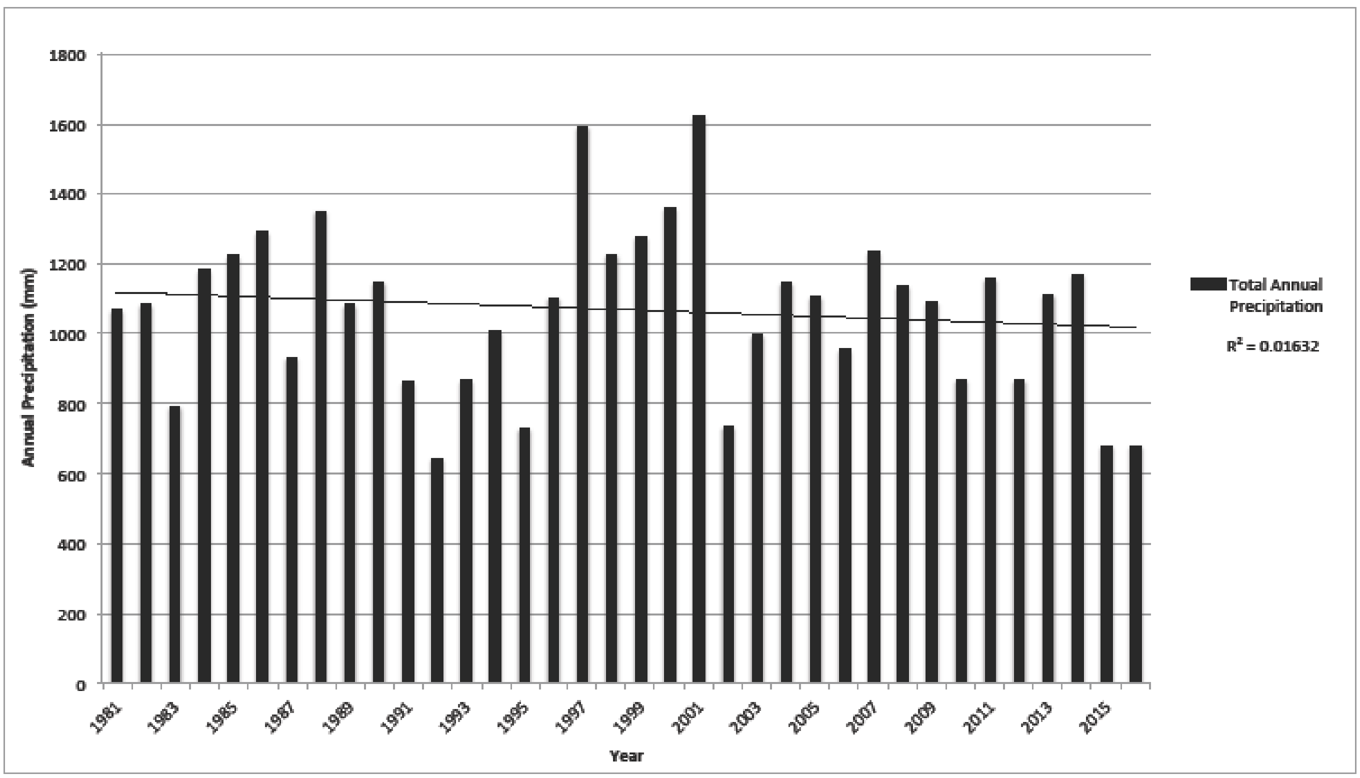
Figure 1. Study Area Map of GNP and its Location within Africa



Sample sites 1-6 are marked for the repeat photography locations.

In 1920, during the time of the Portuguese colonization of Mozambique, Gorongosa was set up as a Game Reserve. Gorongosa was established as a national park by the Portuguese government in 1960. However, shortly thereafter, in 1964, the war for independence from Portugal began and lasted until 1974, when Mozambique was declared independent. Based on aerial surveys at the end of the 1960's and early 1970's an estimated 2,200 elephant, 14,000 buffalo, 5,500 wildebeest, 3,000 zebra, 3,500 waterbuck, 2,000 impala, 3,500 hippo, and herds of eland, sable, and hartebeest were all found within GNP.[16] These surveys provide the "baseline" for current conservation in the park. In 1977, a civil war broke out and lasted for fifteen years. At various points during the war, the headquarters for each side was within GNP and many battles took place inside the park and at nearby Mount Gorongosa.[17] These wars resulted in GNP losing from 90 percent to 99 percent of its large animal populations.[18] In addition to this, during the period from 1993 to 1996 a variety of illegal hunting ventures existed within GNP and killed even more of the already devastated wildlife populations. This extreme loss of wildlife diverges from natural systems processes, and these population numbers in Gorongosa are opposite of what was observed in most of southern Africa's protected areas during this period (1970-2005).[19]

Figure 2. Total Annual Precipitation Amounts Interpolated Over the Park 1981-2016



Source: Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)

In 2004, the Gorongosa Restoration Project began as a partnership between the Carr Foundation and the Mozambican government. Gorongosa has adopted a management and development model that balances conservation with the needs of the people surrounding the park by increasing tourism, science, and community investment in the park.[20] As part of the conservation effort, park managers have been conducting baseline ecosystem monitoring, which is why managers are interested in determining how vegetation is changing within the park. In 2010, three years into the Gorongosa Restoration Project, an aerial survey was conducted and found that wildlife within the park had increased by about 40 percent since the beginning of the restoration project.[21]

Methods

This study analyzed ground based photographs from at least two dates, one from the 1900s and the second from 2012, to describe the vegetation change in GNP, which has a large digital archive with several hundred landscape photos and many hours of video. After sorting through the photographs and videos, nineteen photographs or still captures of the video from six sites around GNP were selected as these were deemed useable, meaning the location was identifiable and the photos could be repeated today.

During the 1930s several structures were built inside the park, some of which at least still partially stand today. The majority of the photographic evidence presented here focuses on the area around these structures because these were the most accurately identifiable. One of the best examples of this is the "Lion House" on the edge of the floodplain. Many of the photographs are focused around the Lion House because this was one of the main areas tourists would visit within the park. When these structures were built, the area directly under them was cleared, and therefore the vegetation was altered. The structures and roads then fell into disarray with the political turmoil and fighting.

There are seventy-two years of data presented in this study, though not at a consistent time interval. The earliest photograph analyzed was from 1940, and the dates then range through the early 1970s (see tables for the exact year of each photograph). Each of the sites of the earlier images was located in July 2012 (during the dry season) and a "repeat" photograph was taken. To insure as much compatibility as possible these "repeat" photographs were taken from a similar vantage point and distance as the original photograph, and a similar focal length and angle was also used. In the historical archive, the exact camera and lens were not recorded. Therefore, a basic 18-55 mm lens was used, unless otherwise specified. In certain cases that were further away a longer lens of 70-300 mm was used. Seasonality was accounted for because the park is closed during the rainy season, so all comparison photographs were from the dry season in the past. Using shadows, the time of day was matched between the historical photographs and the shots taken in 2012. At each of the sites a GPS location was also recorded. Vegetation plot analysis and qualitative field notes, including dominant vegetation types, and overall landscape type were also recorded (Table 1) for the current analysis.

The changes in the photographs were quantified by using *Edwards tabular key to structural groups and formation classes* to determine what habitat cover was present at each of the dates (Table 1).[22] This key includes Dominant Height Class, Total Plant Cover >0.1 percent, and Total Plant Cover <0.1 percent (bare ground) to distinguish between Woodland (tree dominated), Bushland (tree and shrub dominated), Shrubland (shrub dominated), Grassland (grass dominated), and Herbland (herb dominated) in southern Africa. The same research method was implemented by the first author throughout the analysis to ensure consistency, and the process was as follows: historical and July 2012 photographs were placed side-by-side and broken into

Table 1. Edwards Tabular Key for Vegetation Structure used for the Vegetation Samples Taken at Each Repeat Photography Site.

Tabular key to structural groups and formation classes (Edwards 1983)

Dominant Height class	*Total plant cover >0.1%*				Total plant cover <0.1%
	Total tree cover >0.1%; shrub cover <10% if >1m high **A. Forest & Woodland** *Total tree cover*				**F. Desert Woodland** *Trees dominant*
	100-75% *0-0.1ø*	*75-10%* *0.1-2ø*	*10-1%* *2-8.5ø*	*1-0.1%* *8.5-30ø*	
Trees >20 m	1. High forest	5. High closed woodland	9. High open woodland	13. High sparse woodland	57. High desert woodland
Trees 10-20 m	2. Tall forest	6. Tall closed woodland	10. Tall open woodland	14. Tall sparse woodland	58. Tall desert woodland
Trees 5-10 m	3. Short forest	7. Short closed woodland	11. Short open woodland	15. Short sparse woodland	59. Short desert woodland
Trees 2-5 m	4. Low forest	8. Low closed woodland	12. Low open woodland	16. Low sparse woodland	60. Low desert woodland
	Total tree cover >1%; shrub cover >10% & > 1m high **B. Thicket & Bushland** *Total tree cover*				
	100-10%; 0-2ø		*10-1%; 2-8.5ø*		
Trees 5-10 m & Shrubs 2-5 m	17. Short thicket		19. Short bushland		
Trees 2-5 m & shrubs 1-5 m	18. Low thicket		20. Low bushland		
	Total tree cover <0.1%; shrub cover >0.1% *or tree cover up to 1% & shrub cover >10% & >1m high (closed shrublands)* **C. Shrubland** *Total shrub cover*				**G. Desert Shrubland**
	100-10%; 0-2ø	*10-1%; 2-8.5ø*	*1-0.1%; 8.5-30ø*		*Shrubs dominant*
Shrubs 2-5 m	21. High closed shrubland	25. High open shrubland	29. High sparse shrubland		61. High desert shrubland
Shrubs 1-2 m	22. Tall closed shrubland	26. Tall open shrubland	30. Tall sparse shrubland		62. Tall desert shrubland
Shrubs 0.5-1 m	23. Short closed shrubland	27. Short open shrubland	31. Short sparse shrubland		63. Short desert shrubland
Shrubs <0.5 m	24. Low closed shrubland	28. Low open shrubland	32. Low sparse shrubland		64. Low desert shrubland
	Total tree cover < 0.1%; shrub cover <0.1%; grass cover dominant and >0.1% **D. Grassland** *Total grass cover*				**H. Desert grassland**
	100-10%; 0-2ø	*10-1%; 2-8.5ø*	*1-0.1%; 8.5-30ø*		*Grasses dominant*
Grasses > 2 m	33. High closed grassland	37. High open grassland	41. High sparse grassland		65. High desert grassland
Grasses 1-2 m	34. Tall closed grassland	38. Tall open grassland	42. Tall sparse grassland		66. Tall desert grassland
Grasses 0.5-1m	35. Short closed grassland	39. Short open grassland	43. Short sparse grassland		67. Short desert grassland
Grasses <0.5m	36. Low closed grassland	40. Low open grassland	44. Low sparse grassland		68. Low desert grassland
	Total tree cover < 0.1%; shrub cover <0.1%; herb cover dominant and >0.1% **D. Herbland** *Total herb cover*				**H. Desert herbland**
	100-10%; 0-2ø	*10-1%; 2-8.5ø*	*1-0.1%; 8.5-30ø*		*Herbs dominant*
Herbs > 2 m	45. High closed herbland	49. High open herbland	53. High sparse herbland		69. High desert herbland
Herbs 1-2 m	46. Tall closed herbland	50. Tall open herbland	54. Tall sparse herbland		70. Tall desert herbland
Herbs 0.5-1m	47. Short closed herbland	51. Short open herbland	55. Short sparse herbland		71. Short desert herbland
Herbs <0.5m	48. Low closed herbland	52. Low open herbland	56. Low sparse herbland		72. Low desert herbland

Edwards D 1983. A broad-scale vegetation classification of vegetation for practical purposes. Bothalia 14(3&4): 705-712.

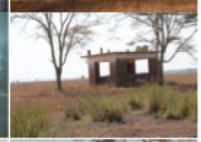
four quadrants with a grid overlay. Then percentages of each type of vegetation were estimated in each quadrant by visual quantification, summed, and recorded. The percentage change over time was then calculated using the formula:

$$Percent\ Change = \left(\frac{(2012\ Percent\ Cover\ - Historic\ Percent\ Cover\ )}{Historic\ Percent\ Cover}\right) * 100$$

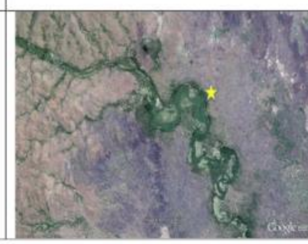
Results

The data from the estimates of vegetation cover show that overall tree cover has increased from 1940 to 2012 (Figure 3). The historic photographs have an average of 25 percent tree cover, whereas the new photographs show an average of 40 percent tree cover. This is an average increase of 15 percent through time. The exception to this is in the second of the three photographs 15 Chitengo (Site 4, the base camp of the park) and the photographs taken at the location named the Hippo House (Site 6) where there was a loss of vegetation cover.

Table 2. Repeat Photographic Sites

Site Number	Name	Photographs: Historic	2012	Tree Cover Percent Change	Google Earth Imagery
1	Lion House 1940			20->80=+300%	
	1957			20->30=+50%	
	1957			5->20=+300%	
	1960			5->10=+100%	
	1960			2->20=+900%	

1	1960		10->30=+200%	
	1963		2->10=+400%	
	1963		15->75=+400%	
	1963		2->45=+2150%	
	1963		10->60=+500%	
	1972		10->30=+200%	
2	**National Park Gate** 1957		70->80=+14%	
3	**Bue Maria** 1957		30->40=+33%	

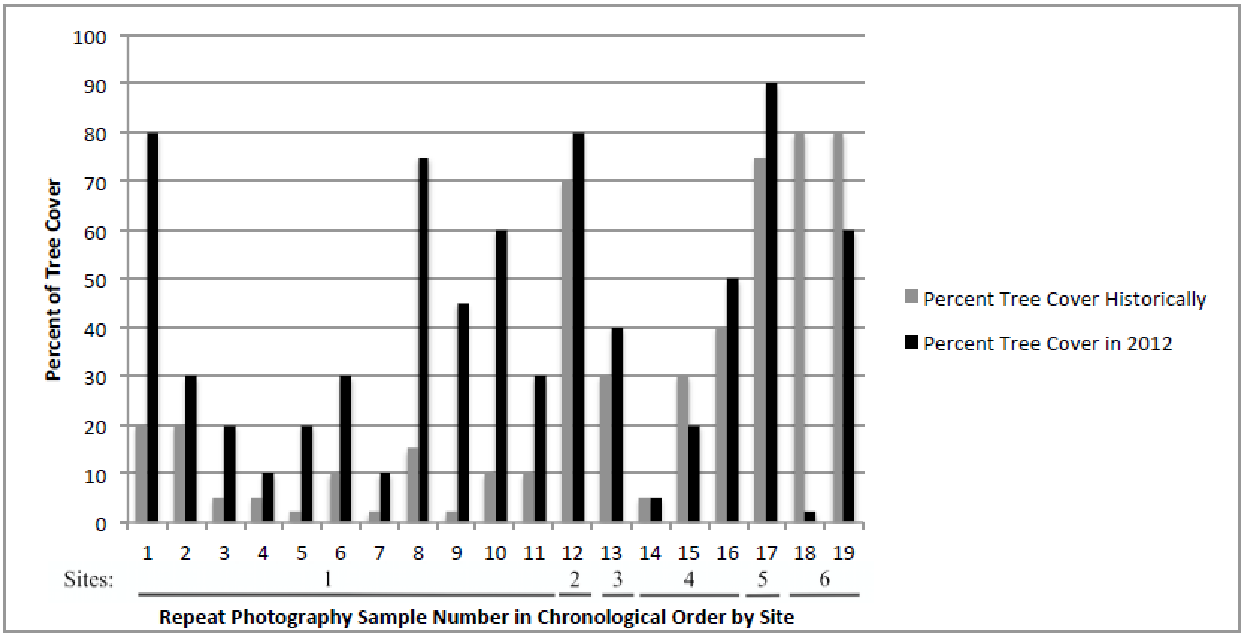
4	**Chitengo** 1964 1967 1967		5->5=0% 30->20=-33% 40->50=+25%	
5	**Bunga Inselburg** 1965		75->90=+20%	
6	**Hippo House** 1970 1972		80->2=-97.5% 80->60=-25%	

Note: Sites, with name, year taken, photographs analyzed, percent tree cover recorded in historic photography and 2012 photograph and percent change, and a 2012 Google Earth Image of each site, with the star representing where the site is. (For details of where the site is spatially within the park, see Figure 1.)

The photographs at Site 1 were taken on the edge of floodplain, where the "Lion House" still stands and four cabins used to stand (Table 2). At site 1 in a 1960 photograph, the majority of the shot is low closed grassland and behind that is short closed woodland. This area may have been cleared previously to allow construction of these structures. From this perspective in 2012, tree growth is prominent. This area is now classified as closed short woodland. The dominating genus is *Vachellia* (previously *Acacia*), and the dominant species is *Vachellia xanthophloea* (fever tree). These trees have grown in closer to the site of the original structures, though only the foundations remain today. The grass composition has remained similar.

The photograph taken at Site 2 was just outside the National Park gate (Table 2). In a 1957 photograph, there was a much lower density of trees in the background with a significantly taller bare tree rising up above the canopy in the background. From this perspective in 2012, there are several larger branches in the foreground, and there are more trees and scrub on either side of the road just inside the gate. While both of these photographs would have vegetation classified as tall closed woodland, the tree cover has greatly increased in density in the recent image.

Figure 3. Percent of Tree Cover in GNP, at the six selected sites



Note: Percent of tree cover determined from 19 photographic sample pairs, beginning in 1940 to 2012 (For order of site dates, see table 2 above).

The photograph taken at Site 3 was at the old Pungwe River crossing just outside the park gates (Table 2). In a 1957 photograph, the site contained some bare ground with tall closed shrubland with short closed woodland behind that. This area was previously cleared in order to make a roadway to the original entrance into the park before the current paved road was created. From this perspective in 2012, grass growth is prominent, and this area is now classified as tall closed grassland with tall open woodland behind it. The grass composition was fairly homogenous in 2012. The area around the old river crossing is now used for agricultural production.

The photograph from Site 4 is of Chitengo, which is the center of human activity in the park (Table 2). In a 1967 photograph, there are several large trees in both the left and right of the frame. A photograph taken from the same perspective in 2012 shows that the tree closest to the concrete on the left hand side is missing. However, when we look at the next image comparison, we can see that there are overall more trees in 2012, and the trees that are there are larger and denser.

The photograph from Site 5 is an area that contains the Vunduzi River in the foreground with the Bunga Inselbergs and Mount Gorongosa in the background (Table 2). At site 5, in a 1965 photograph, there was open short grassland a few hundred meters on either side of the Vunduzi River. This grassland was bordered by short closed woodland. When this shot was retaken in 2012, riparian vegetation has filled in the area around the Vunduzi River. Further out from the river vegetation density and coverage increased into a short bushland, which is a result of shrub encroachment. Some of the taller trees have been replaced with shorter bushes.

The photograph taken at Site 6 was at the Hippo House, alongside Lake Urema (Table 2). In a 1970 photograph, the site contained many tall trees, and was classified as tall open woodland. At the time this area was used as a lunch spot for tourists in the park. In 2012, all of the trees have disappeared. Even the scrub palms have largely been eliminated. Left now is ground with very short grass cover, and a few taller patches of grass.

Discussion and Conclusion

Until recently, we were limited to ground-point and aerial photographs for spatial-temporal studies of landscape change across GNP. However, this research is unique in that it provides a much longer timeframe and finer spatial resolution than most imagery-based studies can. It does however find similar trends to recent studies, such as Daskin et al. (2015) who also found increased tree cover throughout the park landscape. Unlike other parks in the region, we see an increase in tree cover and not shrub encroachment. As mentioned earlier, shrub encroachment has a variety of negative impacts on ecosystems, so this increase in tree cover may indicate that GNP vegetation is healthier relative to other parks in the region, as a result of the unique situation of removal or herbivory in their park during the wars. As such, this provided an unbelievable natural experimental situation for herbivory removal impacts and also highlights the importance of such tools as repeat photography which provides a much longer time frame for study. This also provides an excellent basis for park management, as clearly for tourism parks need to maintain wildlife numbers but also ensure maintenance of the larger ecosystem health. This longer-term study provides an exciting and underutilized approach on which management and future plans can be based. Repeat photography approaches should be used across a suite of park landscapes where historical photographic datasets exist in order to add a different "on the ground" perspective, get longer-term data (pre-dating satellites), and finer temporal resolution going forward, as well as much finer spatial resolution. Utilizing this technique can also target specific areas of interest. Given the new digital age and the progress of tourism in this park, many photographs are now being taken and stored for potential future use.

As already noted, this study shows, via a comparison of historic photographs to ones taken in 2012, that tree cover has increased on average from 25 percent to 40 percent (15 percent overall) over the last seventy-two years across Gorongosa National Park. However, this study did not capture specific evidence of shrub encroachment; rather, the growth of the tree cover was quite clear overall.[23] Even though there are similar savanna landscapes throughout the lower part of the park, we cannot make blanket statements about the entire park. The individual areas studied do offer great insight into general conservation patterns and can assist managers in making decisions. Aside from providing ecological baselines, managers are also interested, from a historical perspective, in seeing how the park has changed over the last seventy-two years. There are some areas in the park that demonstrated extensive growth of vegetation, like the Lion House with trees, the Pungwe River crossing with trees, and the Bunga Inselburgs with riparian trees and also shrubs. Hippo House looked very different in that there was almost a complete loss of tree cover.

Multiple factors may contribute to changing vegetation structure. One factor is management. For example, in the repeat photography of the Lion House, it may be the case that

Vachellia were present until humans built infrastructure. The National Park gate and Chitengo are also managed areas that have been maintained in a similar way throughout history, especially given that the Restoration Project has reinstated tourism in the park. At the Bue Maria River crossing, what was once a maintained road has been abandoned, but part of the area is now devoted to agriculture as well. Other factors may be more natural. In the repeat photograph of Mount Gorongosa with the Vunduzi River and Bunga Inselbergs, we saw a great deal of change over time (Table 2). The source of this river is radial flow from Mount Gorongosa.[24] As evidenced in the photograph, the river has meandered further to the south (to the left in the photo in Table 2) since 1965. This may suggest a change in the flood regime of this river from the mountain, which in turn affects the distribution of rich soil and riparian and floodplain associated vegetation around the river.[25] The repeat photograph of the Hippo House showed that there has been tree cover loss. Given the history of this area, it is unclear whether this area was cleared during the war by military forces to better use this house on stilts as a watchtower, or if excessive flooding from the Lake is responsible for this loss of trees.[26] Regardless of the reason, the area has not returned to tree cover and so is more likely a natural change and highlights one of the few areas of tree decline, which is mostly likely due to water.

The landscape of GNP is sculpted by numerous drivers of spatial heterogeneity including: herbivory, climate variability, and fire.[27] Large animals, such as elephants, are at least partially responsible for the management of *Vachellia* seedlings through browsing and trampling.[28] In a study in Tanzania, it was found that decreasing the number of herbivores (due to poaching) led to an increase in shrub and tree vegetation.[29] During the War for Independence and civil wars, 90-99 percent of all the large mammals in Gorongosa were extirpated.[30] Managers have been implementing a plan to increase the number of megafauna (mostly herbivores, such as elephants, hippos, buffalo, and eland) to maintain vegetation and overall health of the ecosystem. As of 2015, the number of herbivores from the beginning of the project in 2007 has increased by 40 percent.[31] Therefore, it will be critical to continue to monitor this landscape as wildlife numbers are increased in an attempt to return the park to its earlier floral and faunal state, which is one of the primary goals of the GNP management team.

Another one of the main drivers in these savanna systems is climate, including precipitation and temperature.[32] Changes in precipitation can contribute to changes in land cover type.[33] In this park, there is a mean annual precipitation of ~1,000 mm from 1981 to 2016 (Figure 2), (with a minimum total annual precipitation of ~650 mm in 1992 and ~1625 mm in 2001). Given the slight decrease in total annual precipitation through time, this park may be susceptible to some land cover change. However, research has shown that the main climate driver in landscapes below 700mm mean annual precipitation (MAP) is precipitation.[34] In these lower precipitation zones, there is a strong linear relationship between metrics of biomass (for example, spectral-based indices such as NDVI) and precipitation.[35] In the transition zone of 700-950mm MAP both precipitation and temperature co-dominate the vegetation cover. Though above 950mm MAP, temperature and fire dominates the landscape pattern. Precipitation in Gorongosa National Park fluctuates near these MAP boundaries, so each of this climate factors (precipitation, temperature, and fire) may play a role in land cover change. Under climate change, these factors should be monitored further.

Fire frequency has shown conflicting impacts of sprouting of vegetation. In general, where fires are more frequent, grass is promoted, and where fires are less frequent, trees are promoted.[36] The dominant tree genus that has increased in the documented sites is *Vachellia* (see Site 1 photos in Table 2). In other studies, *Vachellia* was also found to be one of the primary increasing tree genera and pioneers in Africa.[37] After reconstructing the fire history of GNP over the last half of the 20th century, Daskin et al. 2015 found that fire frequency has not significantly decreased over time.[38] No single driver is responsible for the vegetation mosaic across GNP, but with significant herbivory change, some climate changes, and slightly differing fire regimes, we are potentially seeing a broad scale alteration of the resultant vegetated landscape.

Future research would continue with the utilization of satellite imagery, beginning in the 1980s, in order to extend the spatial extent. Time series metrics and further discrete data classification of imagery would be ideal to evaluate moderate-term (over the last 30 years) vegetation change and the changing pattern of cover across the entire landscape.

Acknowledgements

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Notes

1 Chapin 2002; Monserud et al. 1993.
2 Feng and Fu 2013; Ciais 2009.
3 Chapin, 2002
4 Andela et al.,2013; Campo-Bescos et al. 2013; Archer et al. 1995; Van Auken 2000; Bond et al. 2003; Asner et al. 2004.
5 Skarpe 1992.
6 Campbell and Child 1971; Ringrose et al. 2008.
7 Vogel and Strohbach 2009.
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13 Byers 1987; Crimmins and Crimmins 2008.
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15 Ringrose et al. 2008.
16 Tinley 1977.
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24 Tinley 1977.
25 Richter and Richter, 2000.
26 Stalmans 2012.
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33 Andela et al. 2013; Campo-Bescós et al. 2013; Moleele et al. 2002.
34 Campo-Bescos et al. 2013.
35 Bunting et al. 2017.
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