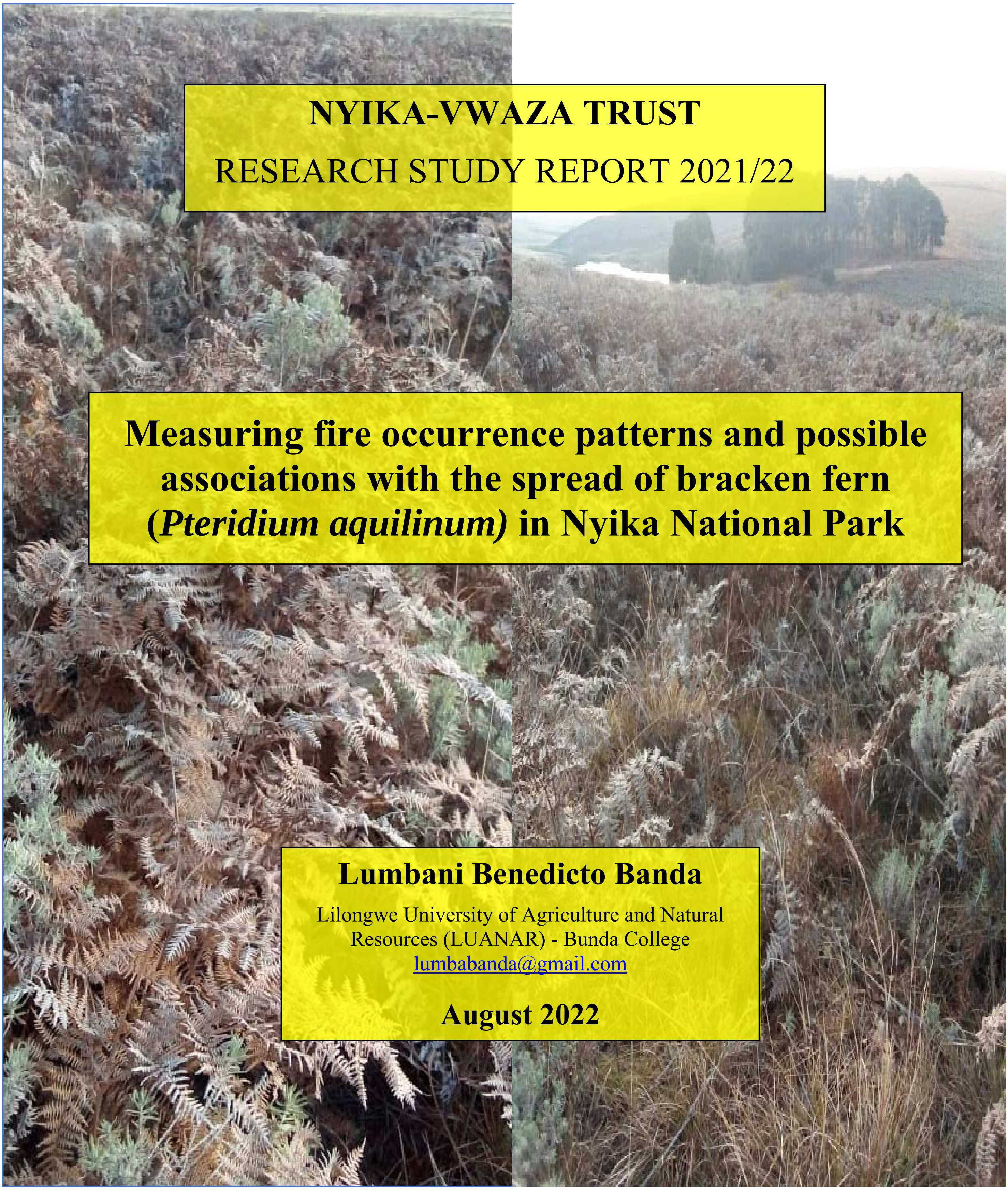

NYIKA-VWAZA TRUST

RESEARCH STUDY REPORT 2021/22

Measuring fire occurrence patterns and possible associations with the spread of bracken fern (*Pteridium aquilinum*) in Nyika National Park

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August 2022

Abstract

In the Nyika National Park prescribed fires are set annually to enhance forage quality and to protect evergreen forest patches. However, concerns have arisen that these fires may increase the spread of the invasive bracken fern (*Pteridium aquilinum*). This study aimed at measuring fire occurrence patterns and their possible association with the spread of bracken. The objectives of the study were threefold: (i) describing fire occurrence frequency between 2013 and 2021; (ii) determining the effects of fire frequency on plant species diversity and composition, and (iii) determining the effects of different fire frequencies on the abundance of bracken fern. Fire occurrence was determined using the Normalized Burn Ratio (NBR) and the differenced Normalized Burn Ratio (dNBR) derived from Landsat satellite images. Vegetation was sampled from unburnt areas as well as low and high fire frequency areas. Hill's numbers were used to compare species diversity, while non-metric dimensional scaling (NMDS) and Permutational Analysis of Variance (PERMANOVA) were used to compare species composition among different fire frequency categories. An analysis of variance (ANOVA) was used to compare the abundance of bracken fern among the fire frequency categories. The results showed that over 70% of the Nyika National Park experienced fires annually between 2013 and 2021. Species diversity was significantly higher in areas of low fire frequency compared to unburnt and high fire frequency areas. Areas of low fire frequency had a distinct vegetation composition compared to areas of high fire frequency. The abundance of bracken fern was significantly higher ($P < 0.05$) in areas of high fire frequency compared to that in unburnt areas and areas of low fire frequency. These results suggest that high fire frequency is associated with the spread of bracken. The study highlights the need to balance between enhancing forage quality while ensuring that fires do not benefit bracken fern, a challenge that will require ecological modelling.

Table of Contents

Acknowledgments

I would like to acknowledge and thank the Nyika-Vwaza Trust for funding the research project. I would also like to acknowledge the Department of National Park and Wildlife (DNPW) for providing the research permit that allowed me to collect data in Nyika National Park. In addition, I would like to thank Mr. Chikwemba, the Park Manager, and the whole management team at Nyika for the logistical support they provided. Special thanks should go to Mr. A. Moyo, Mr. W. Bonongwe, and Mr. Kawonga for assisting me with data collection. Finally, I would like to thank Dr. T.G. Mzumara from the Malawi University of Science and Technology (MUST) and Dr. J.A. Kazembe from the Lilongwe University of Agriculture and Natural Resources for critical comments during the development of the research concept.

1. Introduction

Over the past decades, the use of fire (prescribed burning) to enhance grass forage quality and to protect evergreen forest patches was recommended for the Nyika National Park (Lemon, 1968). Henceforth, fires are set annually at Nyika and have been one of the primary tools that have shaped vegetation characteristics there. Management at Nyika sets prescribed fires from mid-to end of May up to the end of July or August. The application of fire as a management tool is appropriate because the most dominant vegetation type in the park is grass. The effects of fires are less severe in grasslands than in forests because grassland communities recover quickly through regrowth, usually within one year (DeBano *et al*., 1998; Neary and Leonard, 2020).

The application of fire in managing grasslands aims at enhancing the growth of more nutritious grasses (Van Wilgen and Scholes,1997) while removing old undesired plant material (Sweet, 1982; Trollope, 1989). The removal of old plant material and undesired species creates space for the growth of new material (Bailey, 1986). Evidence suggests that fire is crucial for maintaining forage at levels suitable for herbivore grazing (Dublin, 1995). It also influences the grazing pattern of herbivores by reducing the above-ground biomass (Van Wilgen and Scholes, 1997) and distributes herbivore grazing pressure by reducing grazing in recently burnt areas while attracting animals to unburnt areas (Crowder, 1985).

However, an important issue that has gained attention is whether fires can affect the growth of non-native invasive species. Generalizations on this subject are difficult because results are variable. Some suggest that accidental and natural fires can increase the abundance of exotic species (D'Antonio, 2000), while other reports indicate that fire is effective in manipulating vegetation, including in suppressing invasive plant species (DiTimaso, 2006; Keeley, 2001). The effects of fire on vegetation structure are complex because different sources of variation, including heterogeneity, weather, species, and vegetation types, confound them. The interaction among these different sources of variation makes it challenging to generalize results among different regions and at different spatial scales (Penmann *et al*., 2011).

In recent years, concerns have risen at Nyika that the occurrence of fire can be linked to the spread of the invasive bracken fern. Informal observations show that bracken fern is more abundant in areas that experience frequent fires. However, these observations have not been empirically tested, making it difficult to make management decisions. Bracken fern, *Pteridium aquilinum*, is an invasive plant that has spreading underground rhizomes. It forms colonies that hinder the growth of other plants underneath and presents a significant challenge to the management of plant species because of its rapid spread. The coverage of bracken fern at Nyika has been increasing over the years, and by 2017 the coverage of bracken fern was over 20,000 ha (Kanzunguze 2019a, 2019b). The species is difficult to eliminate or control. Even though various efforts, including mechanical control, have been tried, the species continues to spread. A key feature that has made the control of bracken fern a challenge has been a lack of understanding of the factors that influence its spread. Effective control of bracken fern will require a detailed understanding of the factors that affect its spread. An exploration of various causes of the spread of bracken, such as fire regimes and climate, has been suggested (Kanzunguze, 2018). Yet at present none of these factors has been investigated to examine how they relate to its abundance and spread.

This study sought to understand the influence of fire frequency on the abundance of bracken fern on the Nyika plateau. It hypothesized that fire occurrence frequency can explain the spread of bracken. Determining the effects of fire on vegetation structure and the spread of invasive species requires long-term data on areas that have been burnt over the years. However, data on vegetation patches that were burnt over the past years are difficult to find because records were not always kept. Nevertheless, with satellite images, it is possible to create a fire history by detecting areas that were subjected to burning, even for the years when management did not keep records. Therefore, this study aimed at using remote sensing techniques to measure fire occurrence patterns and possible associations with the spread of bracken. It had the following specific objectives: (i) describing fire frequency occurrence between 2013 and 2021; (ii) determining the effects of differential fire frequencies on plant species diversity and composition, and (iii) determining the effects of different fire frequency categories on the abundance of bracken fern.

2. Methodology

2.1 Description of the Study Area

The study was conducted in Nyika National Park in northern Malawi. Nyika lies between $10^{0}15'$ to $10^{0}95'$S and $33^{0}55'$ to $34^{0}05'$E (Figure 1) and is the largest national park in Malawi, covering an area of about 3,200 km^2. Miombo woodlands are the most dominant vegetation covering about

60% of the park while montane grassland and dambos cover about 37% and evergreen forest occupies the remaining 3%. The park is best known for its extensive grasslands and beautiful scenery. The grasslands have the highest proportion of species.

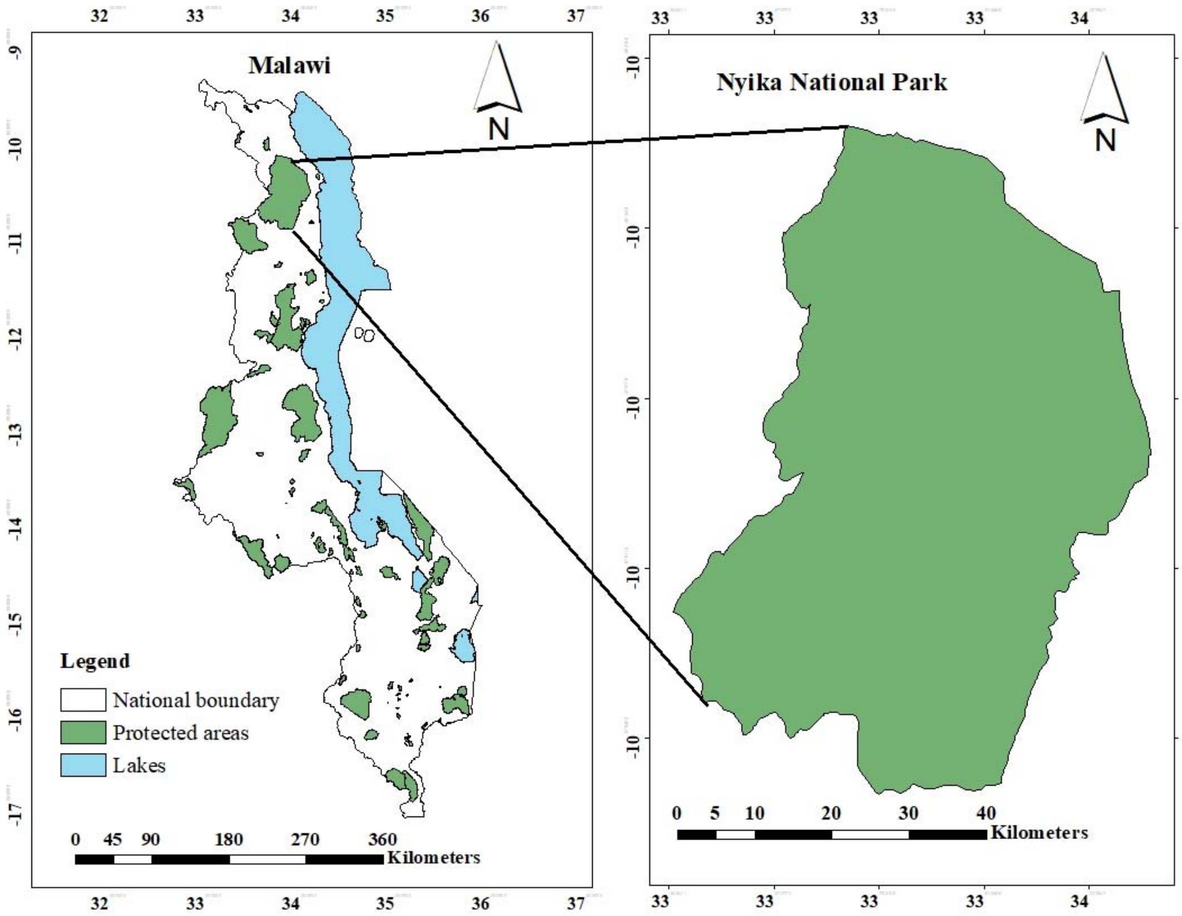

Figure 1: Location of Nyika National Park in the Northern Region of Malawi

2.2 Burn Scar Mapping

2.2.1 Data acquisition and pre-processing

The study used Landsat satellite imagery with a 30 m resolution to create a fire history for Nyika. Images were downloaded from the United States Geological Survey (USGGS) (http://glovis.usgs.gov) website. All images used in this study were from the Landsat 8 (OLI) sensor. The Landsat 8 images have eleven bands with varying spectral characteristics (Table 1).

Table 1: Spectral properties of Landsat 8 images used in the study.

Band Number	Spectral band name	Wavelength (µm)	Resolution (m)
1	Coastal	0.43-0.45	30
2	Blue	0.45-0.51	30
3	Green	0.53-0.59	30
4	Red	0.63-0.67	30
5	NIR	0.85-0.88	30
6	SWIR 1	1.57-1.65	30
7	SWIR 2	2.11-2.29	30
8	Pan	0.50-0.68	15
9	Cirrus	1.36-1.38	30
10	TIRS 1	10.60-11.19	100
11	TIRS 2	11.50-12.61	100

The study used two sets of images – pre-fire images and post-fire images. Acquisition of images for the pre-fire period targeted the month of May, while images for the post-fire period were restricted to the month of September. The choice of these months was based on the onset of controlled burning programs at Nyika, which usually start in May and continues until August. Thus, images for the month of May represented the pre-fire period and images for September represented the post-fire period. Whenever it was not possible to get a good quality image (with low levels of clouds), the nearest date or month with a better image was used. Following these criteria, the study used imagery covering a period from 2013 to 2021 (Table 2). It did not include images for 2016 as it was not possible to get good quality image (<40% cloud cover) for the relevant months. Before use, images were pre-processed by performing atmospheric correction and cloud masking. Atmospheric correction and cloud masking were performed using R-software. Gaps in images resulting from cloud masking were filled using the nearest neighbour interpolation.

Table 2: Description of Landsat images used in the study.

Satellite	Sensor	Path/Row	Spectral resolution	Image acquisition date		Source
				Pre-fire	**Post-fire**	
Landsat 8	OLI	169/67	30m	1/July/2013	19/Sept/2013	USGS
Landsat 8	OLI	169/67	30m	17/May/2014	8/Oct/2014	USGS
Landsat 8	OLI	169/67	30m	5/June/2015	9/Sept/2015	USGS
Landsat 8	OLI	169/67	30m	25/May/2017	14/Sept/2017	USGS
Landsat 8	OLI	169/67	30m	31/July/2018	17/Sept/2018	USGS
Landsat 8	OLI	169/67	30m	2/July/2019	22/Oct/2019	USGS
Landsat 8	OLI	169/67	30m	17/May/2020	22/Sept/2020	USGS
Landsat 8	OLI	169/67	30m	20/May/2021	9/Sept/2021	USGS

2.2.2 Burned area classification and accuracy assessment

To determine burnt areas over the eight years, the study used the Normalized Burn Ratio (NBR) and the differenced Normalized Burn Ratio (dNBR). The NBR index measures a change in the vegetation characteristics, especially in response to fire exposure, and provides a measure of burn severity. NBR and dNBR have been shown to perform well when estimating fire and burn severity (Miller *et al*., 2009; Veraverbeke *et al*., 2010). Computation of the NBR index involves the use of near-infrared (NIR) and shortwave infrared (SWIR) bands (Equations 1 and 2).

$$NBR = \frac{(SWIR - NIR)}{SWIR + NIR} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

$$dNBR = prefireNBR - postfireNBR \ldots\ldots\ldots\ldots\ldots\text{(2)}$$

Where SWIR and NIR are Landsat spectral bands representing short wave infrared and near-infrared radiation, respectively.

The dNBR is a measure of fire severity and is computed based on NBR values obtained from pre- and post-fire images. In this study, the classification scheme of dNBR fire severity values was based on criteria proposed by USGS (Table 3). This fire severity classification scheme was used to classify images into burned areas and unburned areas. Unburned areas were coded 0 and burned areas were coded 1. To compute fire occurrence frequency over the entire study period (2013-2021) the binary coded images were summed. Thus, the last map showed how many times each pixel had been exposed to fire over the eight years. Pixels that were not exposed to fire over the entire period had a value of zero and were categorized as unburned areas. Pixels that had experienced fires once up to four times were categorized as areas of low fire frequency, while pixels that had experienced fires five up to eight times were categorized as areas of high fire frequency.

Table 3: Burn severity levels used in the study (adopted from USGS).

Severity level	dNBR Range
Enhanced regrowth, high(post-fire)	-0.500 to -0.251
Enhanced regrowth, low(post-fire)	-0.250 to -1.01
Unburned	-1.00 to 0.99
Low severity	0.1 to 0.269
Moderate – low severity	0.270 to 0.439
Moderate – high severity	0.440 to 0.659
High severity	0.660 to 1.300

2.2.3 Accuracy assessment

The study adopted a confusion matrix-based accuracy assessment to assess the validity of Landsat dNBR classifications against field data. Data for accuracy assessment was acquired from NASA's Fire Information for Resource Management System (FIRMS). FIRMS provides active fire or thermal hotspot data from satellite observations of the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS). Historical fire data is provided as point shape files of fire hotspots. For MODIS data, the hotspot location represents the centre of 1 km pixel, while for VIIRS data, the hotspot location represents the centre of a 375 m pixel. The study used data from the VIIRS satellite because they represent well fires that occur at small scales, and also have improved night-time performance.

For each year, the study used 120 points for accuracy assessment. The Kappa statistic was used as a measure of accuracy to determine whether the classifications were better than the random classifications (Congalton, 1991). Kappa statistic values that range from 0 to 0.2 represent slight agreement, values between 0.2 and 0.4 represent fair agreement, values between 0.4 and 0.6 represent moderate agreement, values between 0.6 and 0.8 represent substantial agreement, and values between 0.8 and 1 represent the almost perfect agreement (Landis and Koch, 1977).

2.3 Vegetation Sampling

Based on the burn frequency map generated in Section 2.2.2 above, random sampling points were generated for each burn frequency category. Vegetation sampling was designed to follow the sampling points generated. Upon arriving at each sampling point a transect was placed following a direction that was presumed to be along a fire spread direction. On each transect, 20 x 20 m plots were established where five 1 x 1m quadrats were nested. The five quadrants comprised four quadrants laid in each of the corners and one quadrant at the centre (Yohannes *et al*., 2015). A 20 m distance separated all plots on the transect. A total of 75 quandrants were sampled in this study. In each quadrant, all species and their abundances were recorded.

2.3.1 Statistical data analysis

All statistical analyses were conducted using the open-source R-software version 3.6.0 (R Core Team, 2019). To compare species richness and diversity among different fire frequency categories, the study used individual-based species accumulation curves (Neumuller *et al*., 2020). Plant species data for each burn frequency category were aggregated and species accumulation curves were calculated using the iNEXT package (Hsieh *et al*., 2016). To determine the statistical significance between accumulation curves, the overlap of confidence intervals was checked (MacGregor-Fors and Payton, 2013) where overlapping confidence intervals implied no statistically significant difference and vice versa.

To compare plant species composition among the different burn frequency categories, a Non-metric Multidimensional Scaling (NMDS) using the Bray-Curtis distance metric was computed. The Bray-Curtis distances were computed using the "vegdist" function of the Vegan package and the dispersion of each group was calculated using the "betadisper" function (Oksanen, 2007). To determine if there were significant differences in species composition among the three different burn frequency categories, a pairwise permutational multivariate analysis of variance (PERMANOVA) using the "pairwise.adonis" function was conducted (Arbizu, 2020). For comparing species composition among the different burn frequency categories, only common species (≥5%) were included (Wu *et al*., 2013). An Analysis of Variance (ANOVA) with Tukey HSD test was conducted to determine differences in the abundance of bracken and the coverage of grasses among the fire frequency categories.

3. Results

3.1 Accuracy of Landsat Fire Characterization

The classification of burnt areas over the eight years had good accuracy. Overall classification accuracy varied from 85.42% to 95% while the Kappa statistics ranged from 0.71 to 0.89 (Table 4). Good classification accuracy indicated that the classification outputs could be used for subsequent analysis.

Table 4: Accuracy assessment of burnt area classification.

Years	Burn classes	Producer accuracy (%)	User accuracy (%)	Overall accuracy (%)	Kappa
2013	Unburned	75.00	94.74	85.42	0.71
	Burned	95.83	79.31		
2014	Unburned	85.00	96.23	90.83	0.82
	Burned	96.67	86.57		
2015	Unburned	92.50	96.52	94.58	0.89
	Burned	96.67	92.80		
2017	Unburned	90.83	99.09	95.00	0.90
	Burned	99.17	91.54		
2018	Unburned	85.00	100.00	92.50	0.85
	Burned	100.00	86.96		
2019	Unburned	86.67	88.89	87.92	0.76
	Burned	89.17	86.99		
2020	Unburned	89.17	100.00	94.58	0.89
	Burned	100.00	90.23		
2021	Unburned	88.33	90.60	89.58	0.79
	Burned	90.83	88.62		

3.2 Spatial-temporal Fire Occurrence in Nyika National Park

The results showed that most of the Nyika experience fire annually. Over 70% of the park experienced fire every year between 2013 and 2021 (Figure 2, Table 5). Patterns of fire occurrence were different over the years, however, as in most years the eastern part had substantial portions of the unburnt area. Fire occurrence patterns were similar for 2017, 2018, and 2019. During those years, the central and south-western parts of the Nyika had easily noticeable portions of unburnt areas (Figure 2), but most of the southwestern part experienced fire over many years (2014, 2015, 2017, 2020, 2021).

During the eight years studied, six years registered fires that covered over 80% of the Nyika. The extent affected by fire ranged from 2322.97 km^2 (72.58%) to 2835.11 km^2 [88.58%], while the extent of unburnt areas ranged from 365.65 km^2 to 877.79 km^2 (Table 5). The highest proportion (88.58%) exposed to fire was observed in 2015, followed by 2020 (87.39%). The study observed the lowest proportion of the areas exposed to fire was in 2018 (72.58%) and 2019 (79.38%). Overall, even though the location of fires could differ over the years, the size of the area affected by fires was relatively similar in most years.

Table 5: Size of burnt and unburnt areas at Nyika National Park between 2013 and 2021.

	Unburnt area		**Burnt area**	
year	**area in km^2**	**percentage (%)**	**area in km^2**	**percentage (%)**
2013	558.82	17.46	2641.94	82.54
2014	503.45	15.73	2697.31	84.27
2015	365.65	11.42	2835.11	88.58
2017	438.81	13.71	2761.95	86.29
2018	877.79	27.42	2322.97	72.58
2019	660.03	20.62	2540.73	79.38
2020	403.56	12.61	2797.20	87.39
2021	587.02	18.34	2613.74	81.66

A categorization of fire occurrence frequency across the national park revealed that most patches experienced frequent fires between 2013 and 2021 (Figure 3). Vegetation patches that were not burnt over the eight years covered 25.61 km^2 (0.8%). Areas with low fire frequency covered 346.82 km^2 (10.84%), while areas with high fire frequency covered 2828.33 km^2 (88.36%). Vegetation patches that were exposed to low fire frequency were mainly on the eastern part of the park (Figure 3).

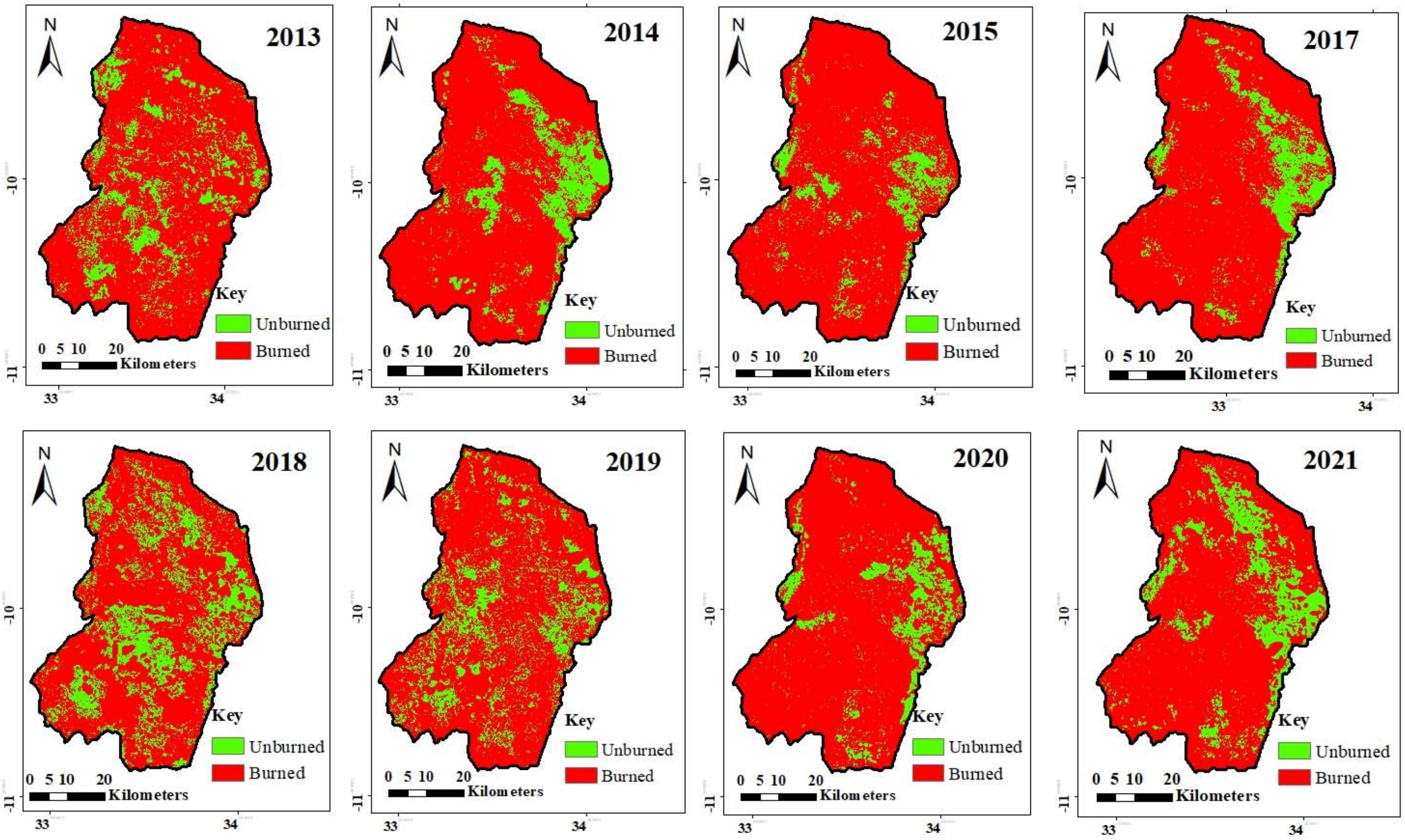

Figure 2: Fire occurrence at Nyika National Park from 2013 to 2021.

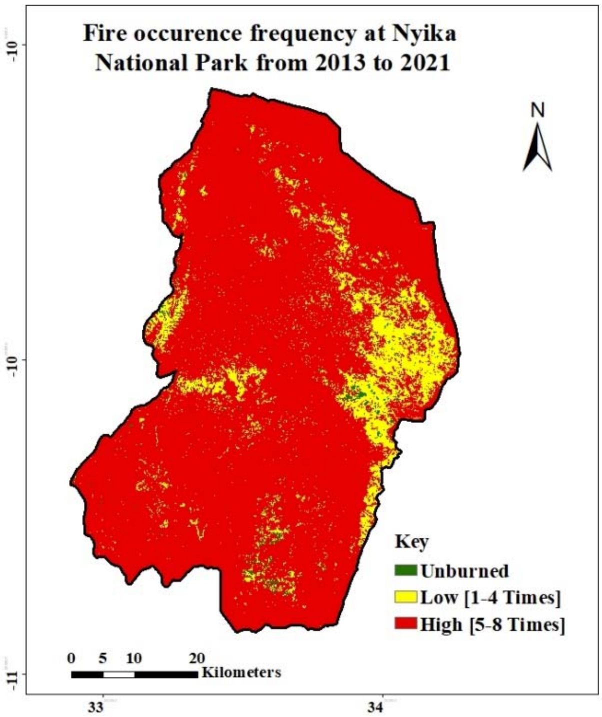

Figure 3: Fire occurrence frequency at Nyika National Park from 2013 to 2021.

3.3 Species Diversity and Composition among Areas of Different Fire Frequency

The study recorded 75 plant species in all plots. In unburnt areas, there were 34 plant species, with 54 species in areas of low fire frequency and 34 species in areas of high fire frequency. A comparison of plant species diversity showed that areas of low-fire frequency had a statistically significantly higher species diversity than unburned and high-fire frequency areas for all orders of Hill's numbers (Figure 4). Areas of high-fire frequency had a significantly higher Shannon and Simpson's Diversity than unburned areas. However, species richness was not significantly different between high-fire frequency and unburnt areas (Figure 4).

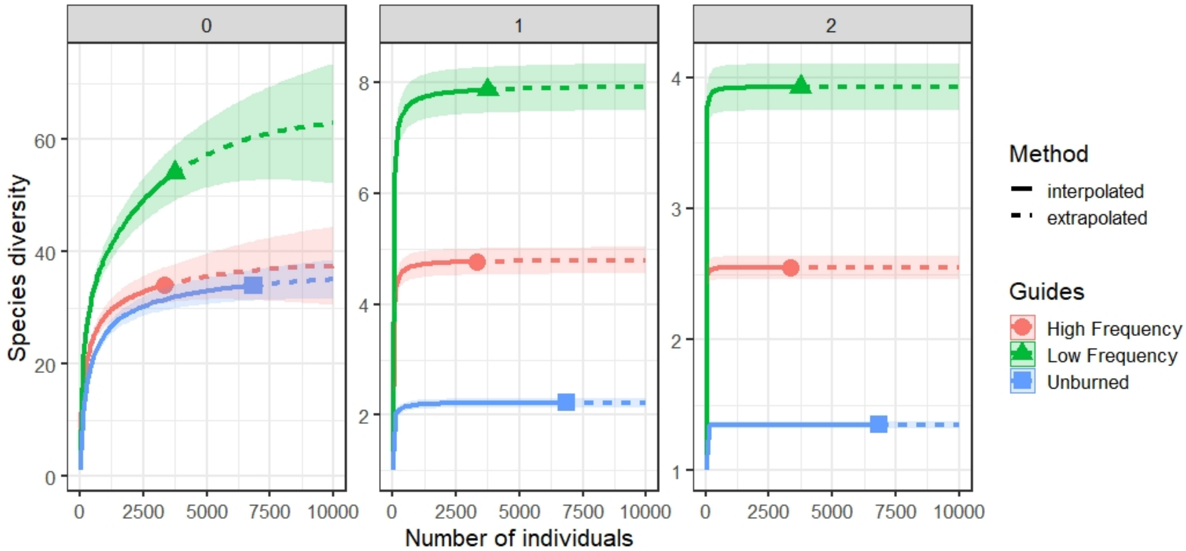

Figure 4: Comparison of plant species diversity among three different fire frequency categories based on measures of Hill numbers of order q: species richness (q=0), Shannon Diversity (q=1, the exponential of Shannon entropy), and Simpson Diversity (q=2, the inverse of Simpson concentration).

Despite differences in species diversity between burned and unburned areas, a PERMANOVA test showed no differences in species composition between burnt and unburnt areas (Figure 5). However, the test showed a significant effect of fire frequency on plant species. The study observed significant differences in plant species composition between areas of low fire frequency and areas of high fire frequency (Figure 5). In plots of low fire frequency, the most abundant plant species were *Coelachne africana*, *Trifolium* spp., *Pteridium aquilinum*, *Haumaniastrum callianthum*, *Galium bussei* and *Loudetia simplex*. While in plots of high fire frequency the most abundant species were *Galium bussei*, *Pteridium aquilinum*, *Coelachne africana*, *Dolichos kilimandscharicus*, *Plectranthus esculentus* and *Pelargonium luridum*. Unburnt areas were dominated by *Galium bussei*, *Pteridium aquilinum*, *Dolichos kilimandscharicus*, *Panicum grandiflorum*, *Plectranthus esculentus* and *Helichrysum herbaceum*.

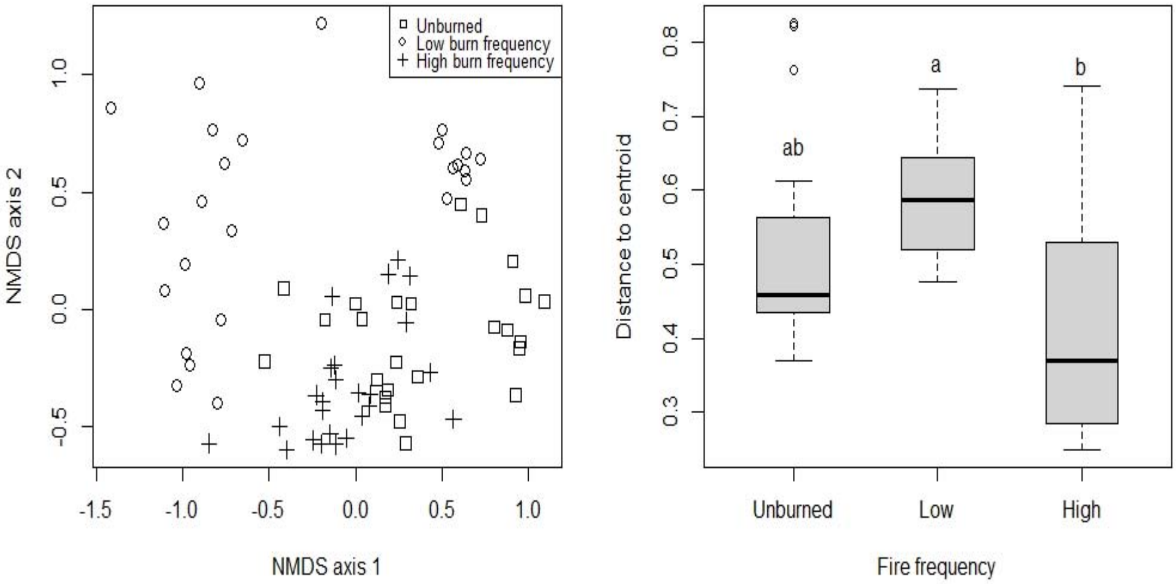

Figure 5: NMDS ordination of species composition (stress = 0.08) showing 75 vegetation plots from three habitats subjected to different fire frequencies (unburnt, low and high). PERMANOVA test showed significant differences in species composition among the three habitat types. Different letters in the boxplot indicate significant differences (P < 0.05) in species composition among the three habitat types.

3.4 Bracken Fern Abundance under Different Fire Frequency Categories

The abundance of bracken fern ranged from 2 individuals to 47 individuals per plot, with an overall mean abundance across all plots of 20 individuals. Findings from this study show that fire frequency had a significant influence on the abundance of bracken among different plots. The abundance of bracken was significantly higher ($P < 0.05$) in areas of high fire frequency than in areas of low fire frequency and unburnt areas. Areas of low fire frequency and unburnt areas were not significantly different ($P > 0.05$) in terms of abundance (Table 6).

Table 6: Abundance of bracken fern among different fire frequency categories.

Burn frequency	Mean abundance
Unburned	14.00 ± 2.51a
Low	15.79 ± 2.71a
High	26.08 ± 2.07b

Means (± standard error) annotated by different letters show significant differences (P < 0.05)

4. Discussion

4.1 Spatial Occurrence of Fire across Nyika National Park

The results showed that most (>70%) of the Nyika National Park experiences fire every year, although the location of fires may differ each year. The area exposed to annual fires is larger than the area in which the management plans to set prescribed fires. Even though the park management may plan to set fires over relatively smaller areas (~40-50%), the fires can get out of control and spread to other areas. Since grasses dominate most of the park, fires spread quickly making them difficult to control. In addition, poachers also set fires to attract animals to specific vegetation patches once vegetation regenerates there. Such fires set by poachers may conflict with the management plan for prescribed fires and may cause undesired effects.

The study also showed differences in the spatial occurrence of fires over the years. This finding suggests that park management adopts shift-burning practices. But some areas are burned frequently, which were categorized as areas of high fire frequency in this study (Figure 3). Some of these areas represent areas that are burnt annually to create fire breaks along pine plantations. Findings from this study confirm that fires are an important vegetation management tool in Nyika National Park.

The study used NBR and dNBR indices derived from satellite imagery to predict fire occurrence. Timing of fire events affects these indices whereby detectable areas can decrease by up to 9% per month after a fire event (Picotte and Robertson, 2011). In addition, pre-fire images for this study targeted the month of May when the study area is often covered by clouds. The quality of the images may have been affected as the amount of light reflected back to the satellite may be low due to the low sun angle (Key, 2005). These factors imply that the study may have over- and under-estimated burnt areas in some places. However, the results are reliable for providing the general patterns of fire occurences and may not significantly deviate from the true values because of corrective measures employed in Section 2.2.1.

4.2 Effects of Fire Occurrence Frequency on Plant Species Diversity and Composition

In this study, burning was associated with higher species diversity. Burnt areas had significantly higher species diversity than unburnt areas. The enhanced regeneration of plant species associated with fires can explain differences in species diversity. During the post-fire period, vegetation recovery is rapid in grassland ecosystems (McDaniel *et al*., 2010; Malkisnon *et al*., 2011). Removal of accumulated litter during burning deposits nutrients in the soil, creates spaces for less dominant species and reduces competition for light, which allows rare species and shade-intolerant species to emerge after fire episodes. Plants that emerge in recently burnt areas are exposed to more light during the early phases of physiological development than those in unburnt areas (Imanuel, 1995), therefore fire provides an opportunity for vegetation development and recruitment due to reduced competition (Wu *et al*., 2013).

However, the results also show that burning frequency has a threshold after which it may reduce species diversity. Results indicate a higher species diversity in low fire frequency areas than in high fire frequency areas. These findings are consistent with those of Collins *et al*. (1995), who found that frequent fires reduced species richness. Frequent fires at the same location may eliminate some species and alter competition interactions against fire intolerant species (Tester, 1996; Peterson and Reich, 2001) consequently reducing species diversity. In grassland ecosystems, frequent burning reduces plant species richness and exposes the soil to solar radiation (Hulbert, 1988).

Findings from this study conform to the prediction of the intermediate disturbance hypothesis (IDH), which suggests that species diversity is maximal at intermediate levels of disturbance (Connell, 1978; Wilknson, 1999). In this study, unburnt areas represent areas with low disturbance where competitive exclusion occurs, consequently reducing the number of species available. High fire frequency occurrence represents high disturbance, where even the most resilient species will be destroyed resulting in low species richness. Low burn frequency represents intermediate disturbance, where fires result in enough destruction to prevent competitive exclusion, allowing the emergence of pioneer species and those that have some competitive advantage in the presence of a disturbance (Bendix, 1998).

Plant species composition differed between areas of low and high fire occurrence frequency, but was not different between unburnt plots and any of the fire frequency categories. These findings suggest that fire frequency is a significant variable that affects species composition, and are consistent with other studies (Boakye *et al*., 2013; Knuckey *et al*., 2016) showing that frequent fires result in a distinct plant species composition. Plant species recorded in areas of high fire frequency represent a group of fire-tolerant and shade-intolerant species. For example, *Pelargonium luridum* inhabits open areas in grasslands and burnt areas (Hyde *et al*., 2022) while *Plectranthus esculentus* prefers areas that are fully exposed to sun or light shade (Bown, 1995). Therefore, the distinct plant species composition observed between areas of low fire frequency and areas of high fire frequency was due to the elimination of fire-intolerant species.

4.3 Effects of Fire Occurrence Frequency on the Abundance of Bracken Fern

The abundance of bracken fern was significantly high in quadrants with high fire frequency compared to those in low fire frequency and unburnt areas. The results suggest that frequent fires are an important variable that governs the spread of bracken fern on Nyika. High fire frequency suppresses the growth of other plant species while creating a favourable environment for survival and the spread of bracken. This is because bracken spores can readily disperse into burnt areas from adjacent non-burnt areas (Silva and Matos, 2006), so they can quickly regenerate during the post-fire period. Bracken also reduces competition with other plants by releasing allelopathic components that hinder their establishment (Pakemann and Marrs, 1992). It has high productivity and accumulates large amounts of litter (Silva and Matos, 2006), which also hinder the establishment of other species.

The survival of perennial plants in the face of repeated fires depends on whether their seeds, meristems, and buds are protected from heat, and on their ability to replenish energy stores and buds after fire events (Whelan, 1995). Many perennial plants can survive under frequent fire regimes if their seeds are protected from heat and post-fire conditions are favourable (Zouhar *et al*., 2008). Bracken has large carbohydrate reserves and several dormant buds in its extensive network of underground rhizomes (Johnson, 2001). These carbohydrates reserves and buds are immune to fire (Silva and Matos, 2006). New shoots sprout from the underground rhizomes so that when the upper part of the plant is destroyed the underground network of rhizomes and carbohydrate reserves forms a refuge, providing bracken with a competitive advantage over other plant species without such vast underground reserves. Even the most severe fires rarely damage plant tissues that are more than 10 cm below ground (Zouhar *et al*., 2008). Bracken rhizomes can penetrate to a greater depth allowing them to survive severe fires. The capacity for plants to resist fire increases as plants mature and if they have an expanding network of underground structures such as rhizomes (Gill, 1995).

The timing of fire events can also explain the association between increasing bracken abundance and high fire occurrence frequency. On Nyika, management conducts early burning between May and August when the bracken is completing its life cycle, as evidenced by the drying up of its leaves. Fires that occur during this period help to clear up dead bracken biomass, opening up space for developing fresh shoots. With large underground food reserves, bracken shoots emerge with vigour. The spread pattern of bracken leaves creates shade for other plant species, especially grasses, suppressing their growth while enhancing its growth. In addition, during the post-fire period when other plant species are re-emerging, they experience grazing and browsing, but bracken fern is much less affected by herbivores because of its toxicity. Grazing reduces the competitive ability of other plant species, while indirectly giving bracken a competitive advantage.

Even though bracken benefits from the prescribed fires, it is important to recognize that fires that are set by management are not aimed at controlling bracken, but rather aimed at enhancing the growth of grasses favoured by large ungulate species. Bracken is an unintended beneficiary of this management practice. This makes vegetation manipulation using fire a challenging task that demands striking a balance between management goals of improving forage quality while minimizing the undesired spread of bracken.

5. Conclusions and Recommendations

The study confirmed that fire is a key vegetation manipulation tool and one of the key factors that influence plant community structure in Nyika National Park. The fires that occur in Nyika National Park play a key role in influencing plant species composition and diversity. Areas subjected to frequent fires have a distinct vegetation composition compared to areas of low fire frequency. This study has shown that fires on Nyika have both positive and negative effects. The positive effects include increased plant species diversity, especially under low fire frequency. While the negative effects are associated with an increased abundance of the invasive bracken fern in areas of high fire frequency.

The findings present park managers with a key challenge, namely how to operate the prescribed fire regimes to enhance forage quality while ensuring that bracken does not benefit. Solving this challenge will require ecological modelling studies that integrate the biological processes of bracken fern and fire regimes. In the meantime, the Department of National Parks and Wildlife (DNPW) should ensure that Nyika managers subject key vegetation patches to low fire frequency, which is beneficial. However, some patches will inevitably still experience high fire frequency, especially areas that are cleared annually to create firebreaks. These areas should be the starting point for bracken control practices because, if they are left unchecked, they can become hotspots for bracken.

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7. Appendices

Appendix 1: Accuracy assessment confusion matrices for burn scar classification.

2013					
Class	**Unburned**	**Burned**	**Total**	**User Accuracy**	**Kappa**
Unburned	90	5	95	0.947368421	0
Burned	30	115	145	0.793103448	0
Total	120	120	240	0	0
Producer Accuracy	0.75	0.95833333	0	0.854166667	0
Kappa	0	0	0	0	0.70833333
2014					
Class	**Unburned**	**Burned**	**Total**	**User Accuracy**	**Kappa**
Unburned	102	4	106	0.962264151	0
Burned	18	116	134	0.865671642	0
Total	120	120	240	0	0
Producer Accuracy	0.85	0.96666667	0	0.908333333	0
Kappa	0	0	0	0	0.81666667
2015					
Class	**Unburned**	**Burned**	**Total**	**User Accuracy**	**Kappa**
Unburned	111	4	115	0.965217391	0
Burned	9	116	125	0.928	0
Total	120	120	240	0	0
Producer Accuracy	0.925	0.96666667	0	0.945833333	0
Kappa	0	0	0	0	0.89166667
2017					
Class	**Unburned**	**Burned**	**Total**	**User Accuracy**	**Kappa**
Unburned	109	1	110	0.990909091	0
Burned	11	119	130	0.915384615	0
Total	120	120	240	0	0
Producer Accuracy	0.908333333	0.99166667	0	0.95	0
Kappa	0	0	0	0	0.9

2018					
Class	**Unburned**	**Burned**	**Total**	**User Accuracy**	**Kappa**
Unburned	102	0	102	1	0
Burned	18	120	138	0.869565217	0
Total	120	120	240	0	0
Producer Accuracy	0.85	1	0	0.925	0
Kappa	0	0	0	0	0.85
2019					
Class	**Unburned**	**Burned**	**Total**	**User Accuracy**	**Kappa**
Unburned	104	13	117	0.888888889	0
Burned	16	107	123	0.869918699	0
Total	120	120	240	0	0
Producer Accuracy	0.866666667	0.89166667	0	0.879166667	0
Kappa	0	0	0	0	0.75833333
2020					
Class	**Unburned**	**Burned**	**Total**	**User Accuracy**	**Kappa**
Unburned	107	0	107	1	0
Burned	13	120	133	0.902255639	0
Total	120	120	240	0	0
Producer Accuracy	0.891666667	1	0	0.945833333	0
Kappa	0	0	0	0	0.89166667
2021					
Class	**Unburned**	**Burned**	**Total**	**User Accuracy**	**Kappa**
Unburned	106	11	117	0.905982906	0
Burned	14	109	123	0.886178862	0
Total	120	120	240	0	0
Producer Accuracy	0.883333333	0.90833333	0	0.895833333	0
Kappa	0	0	0	0	0.79166667

Appendix 2: Selected photos from field work.