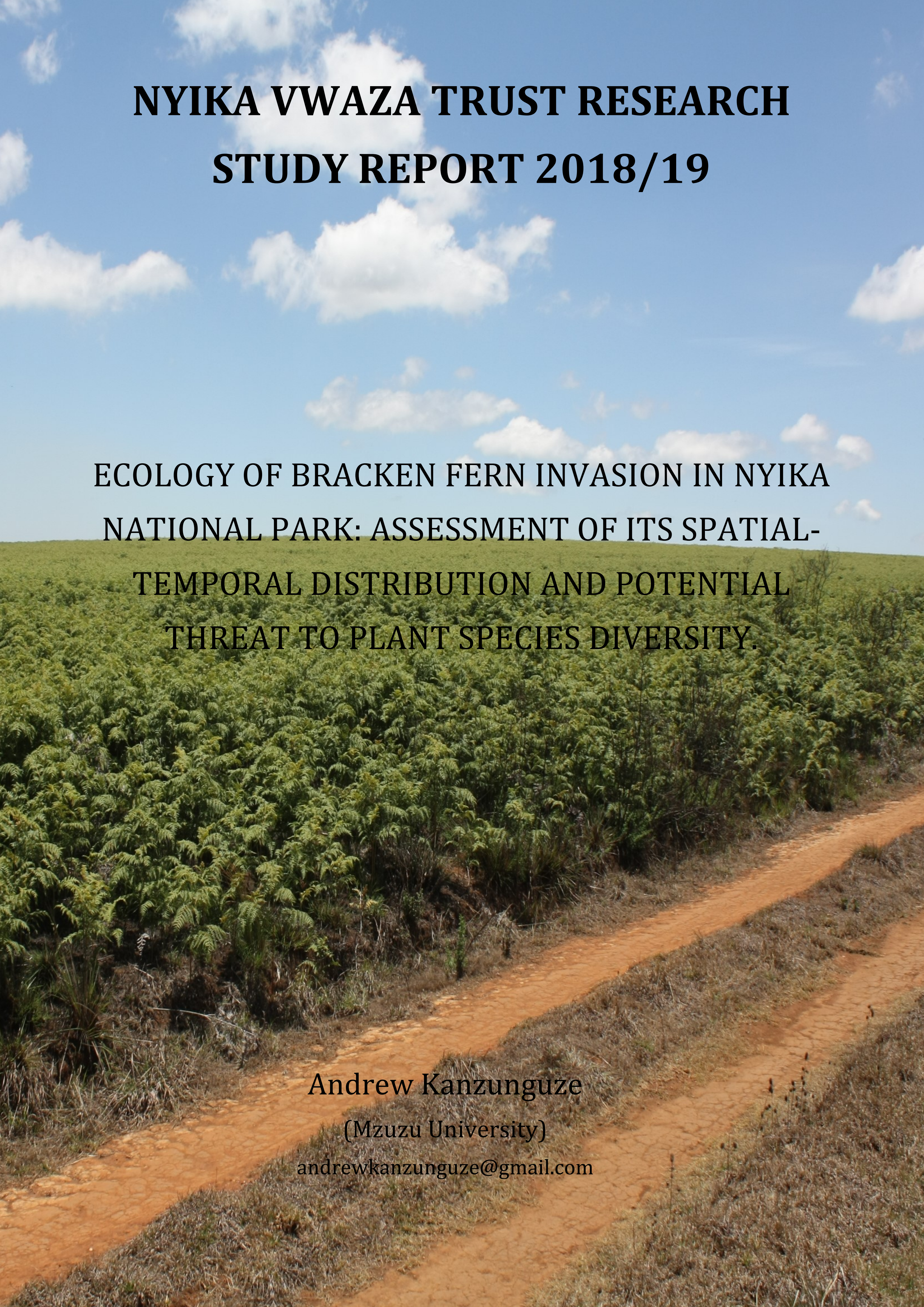

NYIKA VWAZA TRUST RESEARCH STUDY REPORT 2018/19

ECOLOGY OF BRACKEN FERN INVASION IN NYIKA NATIONAL PARK: ASSESSMENT OF ITS SPATIAL-TEMPORAL DISTRIBUTION AND POTENTIAL THREAT TO PLANT SPECIES DIVERSITY.

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SUMMARY

Bracken fern invasion in Nyika National Park (NNP) has been an increasing cause for concern to the Malawi Department of National Parks and Wildlife (DNPW) and other stakeholders of the Protected Area (PA) with respect to future biodiversity conservation efforts. Much uncertainty at the theoretical level on the factors influencing its invasion have been progressively acute because of the absence of information regarding the spatial extent and temporal distribution of the species. To the further discomfort of DNPW management, lack of clarity on the actual threat posed by the invasion on the PA has made it difficult for pragmatic management plans for the invasion to be developed. Thus, the current project aimed at shedding more light on both the spatial and temporal distribution of bracken fern in NNP as well as assessing the impact of the invasion by comparing plant species diversity and soil physical-chemical parameters in bracken invaded and non-invaded areas. Standard remote sensing techniques, biodiversity assessment methods as well as soil analytical procedures were employed to address the study objectives. Results revealed that bracken fern covered 13.7% (20,940.7 hectares) of the entire grassland plateau as of 2017, and was distributed more densely within five kilometres of the pine plantation located at the centre of NNP. The results also showed that the area invaded by bracken fern increased by 121.9% (19,919.4 hectares) between 1986 and 2016 across the grassland plateau, with a 4.06% annual rate of increase. Furthermore, the results indicated significantly ($p<0.01$) lower plant species diversity (richness and evenness) in areas invaded by bracken than non-invaded areas across the grassland plateau, as well as significant variations in soil physical and chemical properties of soils in invaded and non-invaded communities. Given the 4.06% rate of spread between 1986 and 2016 (663.9 hectares per year), bracken could invade the entire grassland plateau in NNP within the next 40 years if left unchecked. This could result in significant alterations to the soil community and consequent loss of grassland plant species diversity in the protected area on which wildlife depends. As it stands, further monitoring on the distribution of the species in the PA as well as research into the factors influencing its spatial-temporal distribution are highly recommended. Additionally, the study recommends that field experimentation of different control options for the invasion should be carried out simultaneous to the research on invasion drivers.

ACKNOWLEDGEMENTS

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Special thanks are expressed to Associate Professor L. Mwabumba, Dr. D. S. B. Gondwe and Mr. G. Z. Nxumayo for their tireless moral and intellectual support throughout the span of the project which was interwoven with my postgraduate studies. Their contribution to this work cannot be overemphasized. Similarly, I also wish to acknowledge the particular support of Jason Gilbertson, Sopani Sichinga, Bob Awali and Justice Mughogho for their support during the critical project stages of data collection, analysis and validation.

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1.0 INTRODUCTION

1.1 Background of the study

Nyika National Park (NNP) is Malawi's largest protected area (approximately 3150Km^2) lying in the northern part of the country, with a small portion extending into the north eastern part of Zambia. The national park is characterized with a beautiful rolling grassland plateau on the interior (i.e. the Nyika plateau), unique floral assemblages that provide habitation to a diverse community of wildlife, and little streams that drain into Lake Malawi interspersed through breath-taking valleys (cf. Burrows and Willis, 2005; Johnson, 2017).

Like most protected areas in Southern Africa, Nyika National Park has not been spared its share of conservation related challenges. Besides the common problems such as poaching and encroachment, plant invasions are becoming a serious concern. Currently, the Nyika plateau is faced with multiple plant invasions from species such as Mexican pine (*Pinus patula*), Black wattle (*Acacia mearnsii*), Himalayan raspberry (*Rubus ellipticus*) and Bracken fern (*Pteridium aquilinum*) besides others (GoM, 2015; Kanzunguze, 2017).

The most pressing of these at the moment is bracken fern (Nxumayo, 2013), which has been described as spreading beyond the central plateau and forming extensive patches within the national park (Nxumayo, 2016). With recent evidence confirming its spread (Kanzunguze, 2018), several stakeholders of the national park are now planning towards developing long term management interventions of this specific invasion (besides the others) in the protected area. It is to complement these efforts that the current study was embarked upon.

Initially, the first phase of this study (Kanzunguze, 2018) demonstrated the feasibility of using remote sensing (RS) and geographic information systems (GIS) in monitoring bracken invasion. During the first phase, one thing that came out very clear was that there was an increase in the amount of bracken since 1986 to 2016. However, aspects such as the spatial distribution of the species vis-à-vis existing features in the area were not thoroughly revealed. Furthermore, the factors that could be promoting the invasion were only speculative.

Instead of delving into explicit elucidation of the factors promoting the bracken fern invasion in the national park during the second phase of the study, increasing agitation amongst managers of the protected area over the invasion prompted otherwise. The issue amongst key stakeholders was on the feasibility of controlling the invasion in light of its notoriety in protected areas elsewhere in the world (cf. Stewart et al., 2005; 2008), as well as the cost implications of carrying out control initiatives for the same across the entire plateau (cf. Nxumayo, 2016). Coupled with the absence of information both on the current spatial distribution of the species as well as effects of the same on important attributes of the national park, management of NNP appeared to be getting disinclined to prioritizing the invasion (Mwiya, 2017). This was especially in light of other problems that have been getting increasing attention in the national park, particularly in relation to human-wildlife conflicts.

The problem expressed by managers can be summarized as a dilemma of risks. On one side, the risk of wasting resources in addressing a perceived invasion threat that is no threat at all. On the other side, the risk of procrastination in implementing an invasive plant management intervention for bracken fern when the threat posed by the species is in fact a serious one than meets the eye at the moment. Knowing the problematic nature of bracken fern in environments similar to NNP (cf. Robinson *et al*, 2010; Berget *et al.,* 2015), ignoring or prolonging this dilemma and/or inattention to the invasion could result in a scenario wherein the ability of the national park to sustain important biodiversity components and functions is heavily undermined or compromised.

Therefore, the second phase of this project as reported herein went a step further in using the same RS and GIS techniques (as in the first phase) in refining both the spatial and temporal distribution of the species on the Nyika plateau. This was done with the purpose of bringing out the extent of bracken fern invasion on the Nyika plateau. Furthermore, an assessment was carried out to determine the extent to which bracken fern could be affecting the grassland plateau by comparing plant and soil characteristics in bracken invaded and non-invaded areas. This was done to allow managers to appreciate and/or vividly conceptualize the severity of bracken fern invasion in NNP. It is therefore the expectation that the findings in this report will help NNP management and all relevant stakeholders in making decisions on when and how best to manage the invasion.

1.2 Objectives

The study determined to reveal the spatial extent and temporal distribution of bracken fern, and also assess the effect of its invasion on plant species diversity of the grassland plateau in Nyika National Park.

1.2.1 Specific objectives

The specific objectives of the study were as follows;

a) To establish the current spatial extent of bracken fern on the grassland plateau in Nyika National Park.
b) To determine the temporal distribution of bracken fern on the grassland plateau in Nyika National Park from 1986 to 2016.
c) To assess the effect of bracken fern invasion on plant diversity in Nyika National Park.
d) To compare soil physical and chemical properties between invaded and non-invaded areas on the grassland plateau in Nyika National Park.

1.2.2 Research questions

The following research questions were used to assess the specific objectives;

Objective 1: To establish the current spatial extent of bracken fern on the Nyika plateau.

i. What is the current coverage of bracken fern on the Nyika plateau?
ii. What is the pattern of bracken fern distribution across the Nyika plateau?

Objective 2: To determine the temporal distribution of bracken fern on the Nyika plateau from 1986 to 2016.

i. To what extent has bracken fern spread in area over the past 30 years on the Nyika plateau?
ii. At what rate has bracken fern coverage changed on the Nyika plateau over the past 30 years?

Objective 3: To assess the effect of bracken fern invasion on plant species diversity on the Nyika plateau.

i. How does plant diversity compare between bracken fern invaded areas and uninvaded grassland areas on the Nyika plateau?
ii. Is vegetation in bracken fern invaded areas similar to the vegetation in uninvaded areas on the Nyika plateau?

Objective 4: To compare soil physical and chemical properties between invaded and non-invaded areas on the Nyika plateau.

i. Are there significant differences in soil physical properties between bracken fern invaded and non-invaded areas on the Nyika plateau?
ii. Are there significant differences in soil chemical properties between bracken fern invaded and non-invaded areas on the Nyika plateau?

2.0 METHODOLOGY

2.1 Study Site

The study was conducted in Nyika National Park located between 10°15' to 10°95'S and 33°55' to 34°05'E (Figure 3.1). It lies at an altitude between 2,100m and 2,600m. It consists of rolling grassland hills interspersed with pockets of montane forest patches at the mouths of valleys, which get steeper away from the central plateau (with slopes up to 1 km wide, and 200 m deep) especially towards the northern and extensively forested eastern escarpments (Burrows & Willis, 2005).

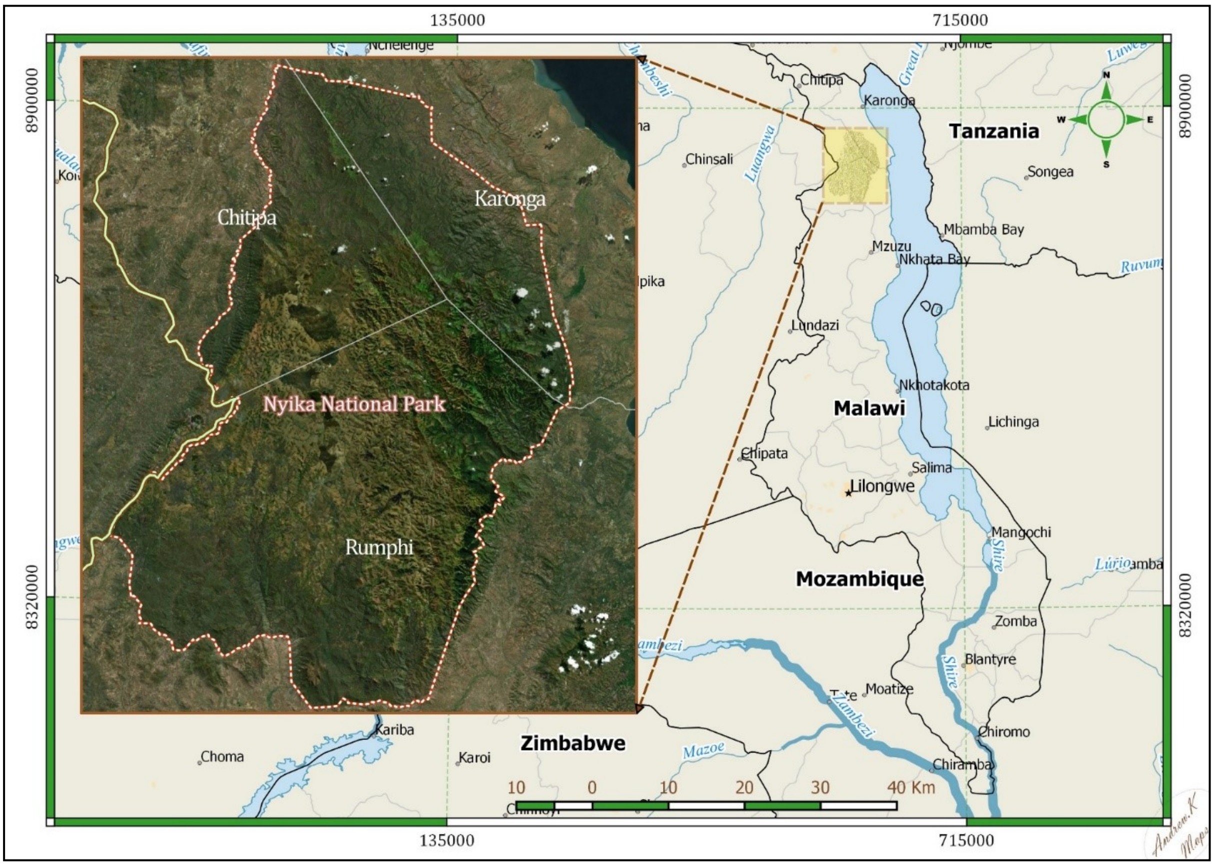

Figure 1: Location of Nyika National Park in Malawi

2.2 Research Design

The research was carried out as a cross-sectional survey, employing both remote sensing and geographic information system (GIS) techniques, vegetation ecology and biodiversity assessment techniques as well as soil analytical methods to address the study objectives.

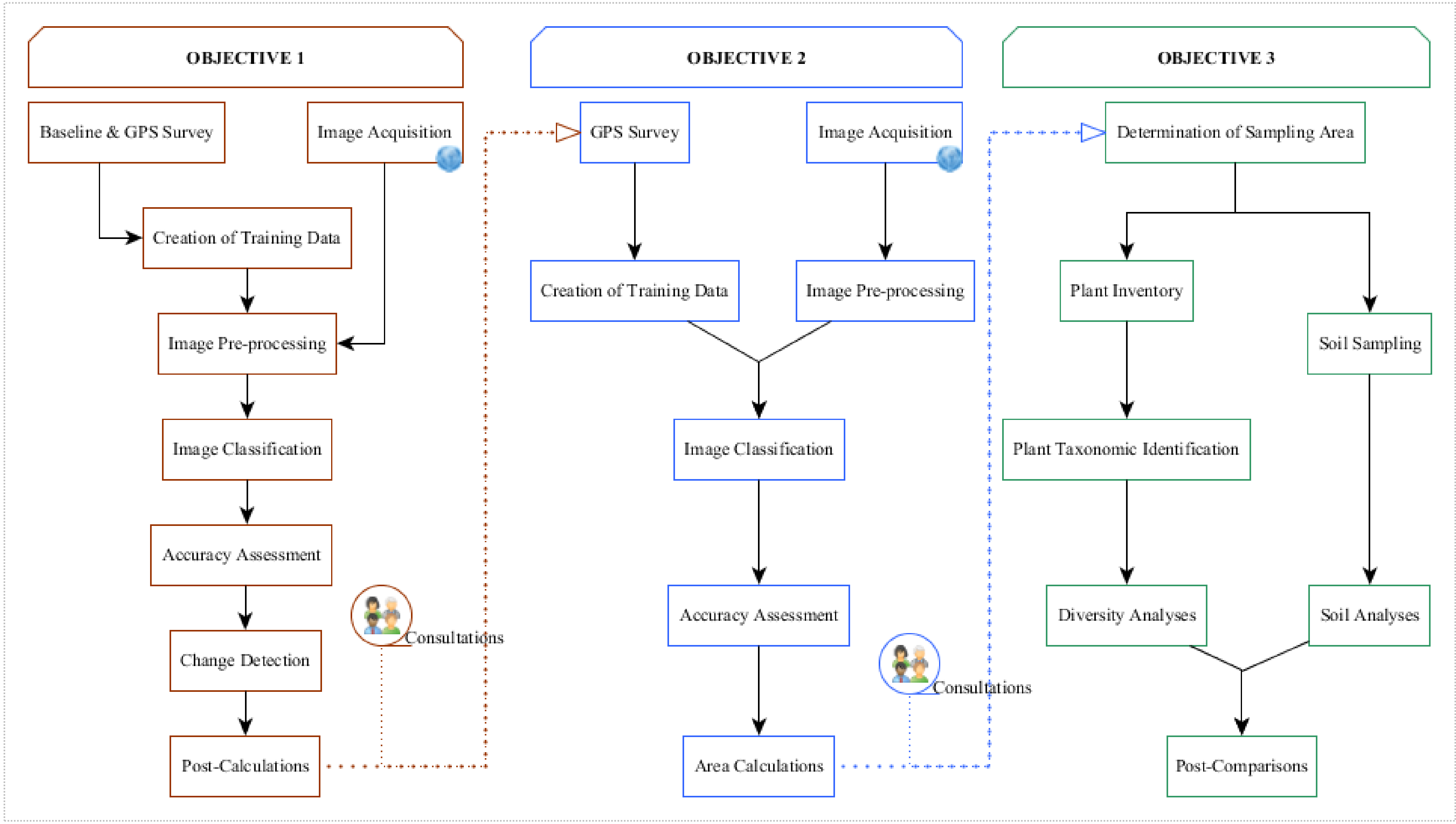

Figure 2: Overall work flow of the study.

2.3 Detection of Bracken fern Invasion on the Nyika plateau

Figure 3.3 illustrates the harmonized methodology employed in establishing the spatial extent and determining the temporal distribution of bracken fern. The objective was largely achieved using remote sensing techniques in geographical information systems.

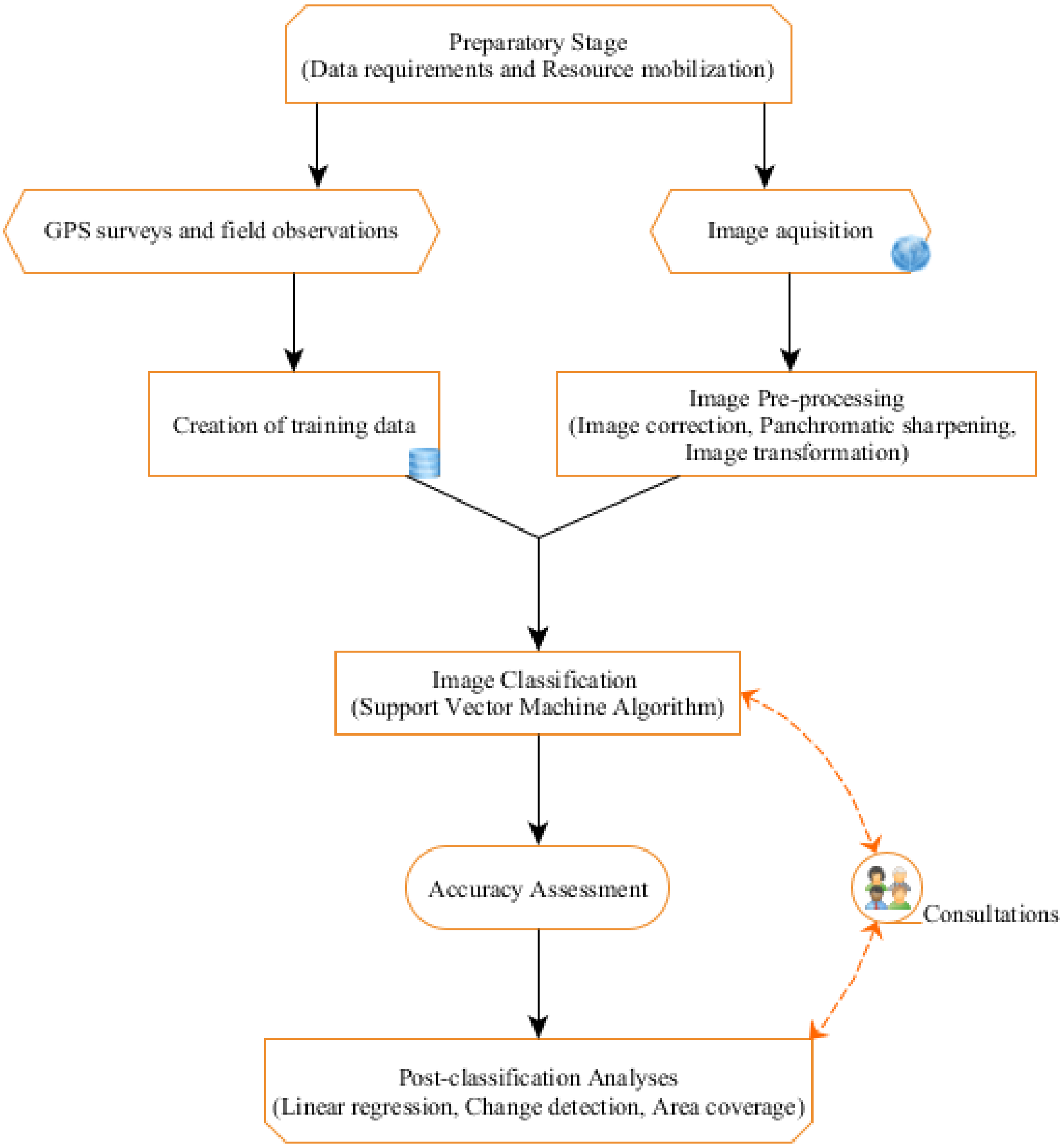

Figure 3: Harmonized methodology for objectives 1 and 2.

2.3.1 Baseline GPS Survey and Creation of Training Data

Field surveys were carried out in September 2016 and December 2017. A Global Positioning System, calibrated to Universal Transverse Mercator (UTM) southern zone 36 of the World

Geodetic System of 1984 (WGS 84), was used to record coordinates of different land cover classes. A coordinate was recorded at a point where a target land cover class covered an area of greater than 900m^2 (30m x 30m) around the recording point. A total of 606 reference points were collected during the surveys (Table 3. 1) and stored in an .xls file format in Microsoft Office Excel 2016 spreadsheet. The coordinates collected in 2016 were used in determining the spread of bracken fern from 1986 to 2016, whereas the coordinates collected in 2017 were used in establishing the spatial extent of bracken fern on the grassland plateau.

Table 1: Reference points (n=606) collected for land cover classes during the baseline GPS surveys in 2016 and 2017.

Land Cover Class	**Description**	**Number of coordinates recorded**	
		2016	**2017**
Fern	A stand with complete bracken fern dominance.	97	44
Forest	Patch of forest e.g. miombos, junipers, firs, eucalyptus and pines.	122	78
Grassland	Upland grassland areas with little woody shrubs available.	57	145
Fire scar	A tract of land scarred by fire with very few herbs and grasses regenerating.	0	55
Water	A water body e.g. dam, lake, river, stream.	8	0
Sub-total		**284**	**322**

The remote ecosystem monitoring assessment pipeline, REMAP (Murray *et al.*, 2018), was used to verify precision of reference points. The stored coordinates were then converted to a .csv file format for data visualization and manipulation in Quantum GIS version 2.18. The data (displayed as points) was then converted and saved as a point shapefile (.shp file format) to be used as training data during image classification.

2.3.2 Image acquisition

The Landsat family of satellite imagery was selected for use in remote detection of *Pteridium aquilinum* because of their cheap acquisition cost (Wulder *et al.,* 2012), ease of processing and manipulation, consistency of data capture over different locations (Zhu *et al*, 2012; Hansen & Loveland, 2012; Vogelmann *et al.,* 2016), and proven reliability in invasive plant detection and monitoring (Huang & Asner, 2009; Kennedy *et al*, 2014; Bradley, 2014). Satellite imagery for the 1986-2016 analysis was accessed and obtained on the 20th February, 2017, whilst that for the 2017 analysis was accessed and obtained on the 23rd January, 2018 both from the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Centre archive at http://earthexplorer.usgs.gov/. Acquisition dates for all the images which covered the entire grassland plateau in Nyika National Park (path/row: 169/67) were obtain on dates within the months of August and September. These months were selected for image acquisition firstly because that is the time when bracken fern patches on the grassland plateau exhibit a reddish-brown to deep-green pigmentation that is distinct from the rest of the grassland plant species, which are usually dry at the same time. Secondly, the months were selected because that is the time when there is the least cloud cover across the Nyika plateau (the hot-dry season), bearing in mind that high cloud cover affects the quality of satellite imagery captured for an area by any remote sensing platform (Johnson, 2017). Table 3.2 summarizes the spectral characteristics of the Landsat imagery used for assessing the spatial extent and temporal distribution of bracken fern in Nyika National Park during this study.

2.3.3 Image pre-processing (correction and enhancement) and Segmentation

The image pre-processing approach by Gilbertson *et al.,* (2017) was adopted in this study. Atmospheric, radiometric and geometric distortions as described in Campbell, (2011) and Mishra *et al.,* (2014) were corrected using the atmospheric and topographic correction (ATCOR) model in PCI Geomatica software. The ATCOR model was calibrated using coefficients provided in the channel metadata files for the satellite imagery. Panchromatic sharpening as described in Li *et al.,* (2017) was next carried out on the corrected imagery using the PANSHARP algorithm to reduce the spatial resolution of all the imagery from 30m to 15m.

Table 2:Spectral characteristics (adopted and modified from **Parece & Campbell, 2013**) of the Landsat images used in the study.

Band ID	Landsat 8 (OLI)	Landsat 7 (ETM+)	Landsat 5 (TM)	Resolution (m)	Band Applications
1	Visible (Coastal) (0.43 - 0.45 µm)	Visible (0.45 - 0.52 µm	Visible (0.45 - 0.52 µm)	30	Coastal and aerosol studies .
2	Visible (Blue) (0.45 - 0.51 µm)	Visible (0.52 - 0.60 µm	Visible (0.52 - 0.60 µm)	30	Bathymetric mapping, distinguishing soil from vegetation, and deciduous from coniferous vegetation.
3	Visible (Green) (0.53 - 0.59 µm)	Visible (0.63 - 0.69 µm	Visible (0.63 - 0.69 µm)	30	Emphasizes peak vegetation, which is useful for assessing plant vigour.
4	Red (0.64 - 0.67 µm)	Near-Infrared (0.77 - 0.90 µm	Near-Infrared (0.76 - 0.90 µm)	30	Discriminates vegetation slopes.
5	Near-Infrared (0.85 - 0.88 µm)	Near-Infrared (1.55 - 1.75 µm	Near-Infrared (1.55 - 1.75 µm)	30	Emphasizes biomass content and shorelines.
6	Shortwave Infrared 1 (1.57 - 1.65 µm)	Thermal (10.40 - 12.50 µm	Thermal (10.40 - 12.50 µm)	30, 60, 120	Discriminates moisture content of soil and vegetation; penetrates thin clouds.
7	Shortwave Infrared 2 (2.11 - 2.29 µm)	Mid-Infrared 2.08 - 2.35 µm	Mid-Infrared (2.08 - 2.35 µm)	30	Improved moisture content of soil and vegetation and thin cloud penetration.
8	Panchromatic (0.50 - 0.68 µm)	Panchromatic 0.52 - 0.90 µm		15	15-meter resolution, sharper image definition.
9	Cirrus (1.36 - 1.38 µm)			30	Improved detection of cirrus cloud contamination.
10	Thermal Infrared Sensor 1 (10.60 - 11.19 µm)			100	100-meter resolution, thermal mapping and estimated soil moisture.
11	Thermal Infrared Sensor 2 (11.50 - 12.51 µm)			100	100-meter resolution, thermal mapping and estimated soil moisture.

Additional information of all Landsat images obtained from the United States Geological Survey Landsat Missions archives (https://landsat.usgs.gov/).

Image transformations as described by Lu and Weng, (2007) were created using ENVI software for amplification and enhancement of landscape features such as vegetation types, bare ground and water prior to differentiation of classes. Some of the transformations carried out amongst others outlined in Gilbertson *et al.,* (2017) and described in Campbell (2011) include the Normalized Difference Vegetation Index-NDVI, Enhanced Vegetation Index-EVI, Normalized Difference Moisture Index-NDMI, Normalized Difference Water Index-NDWI and the Normalized Difference Built Index-NDBI.

Image segmentation was carried out using an object-based approach as described by Hussain *et al*., (2013). The enhanced image transformations were segmented into distinct objects by Multiresolution Segmentation algorithm (MRS) as implemented in Trimble eCognition software, using the object orientated module in PCI Geomatica software. The MRS algorithm groups pixels/data points with similar spectral values into objects using scale, shape, compactness and layer weighting as input parameters (Gilbertson & van Niekerk*.,* 2017). All image bands for the satellite imagery in this study were used as input to the MRS algorithm, with more weighting on green (15%), red (20%), near-infrared (40%), and short-wave infrared (25%) spectral bands. The calibration parameters for the MRS algorithm (scale, shape and compactness) were set to 55 for scale and 0.5 for both shape and compactness after multiple tests and visual assessment to determine what was best for the informational classes.

2.3.4 Image Classification and Accuracy Assessment

In order to extract landcover classes from the satellite imagery, the supervised image classification approach as described in Wulder *et al.,* (2018) was carried out. The Support Vector Machine (SVM) algorithm as described in Maxwell *et al.,* (2018) was used to classify all satellite imagery in PCI Geomatica software. The SVM had its radial basis function kernel set according to recommendations by Hsu *et al*., (2003).

Following the approach by Gilbertson *et al.,* (2017), a 3:2 ratio was employed for splitting data used in image classification and accuracy assessment. Such that 60% of reference data was used for training the SVM algorithm whilst 40% of the remaining data was used for assessing accuracy of the land cover classifications. The object orientated module in PCI Geomatica software was used to run the accuracy assessment and automatically generate error matrixes for the image classifications in this study. The error matrices contained information on overall accuracy (OA) and kappa statistic (Kc) of the entire classification, as well as errors of commission (EC), errors of omission (EO), producer accuracy (PA) and Consumer accuracy (CA) for all land cover classes as described in Lillesand *et al.,* (2008).

2.3.5 Post Classification Analyses

Post classification analyses included extraction of areas (in hectares) of landcover classes using the $.function from the attribute table field calculator in QGIS (Figure 3.5). Afterwards, change detection was carried out using equations adopted from Singh (2013) in determining the percentage of area on the grassland plateau that was infested by bracken fern for each year (Equation 3.1) and the percentage change in area of the grassland plateau invaded by bracken fern (Equation 3.2). Equation 3.3 adopted from McAlpine (2014) was used to calculate the annual rate of bracken fern invasion expressed as a proportion of the invaded area.

$$\text{Percentage coverage (\%)} = \frac{P.aquilinum \text{ area on plateau}}{\text{Area of plateau}} \times 100 \qquad \text{……………………….....}\textbf{Eqn 3.1}$$

$$\text{Percentage change (\%)} = \frac{\text{Area invaded in year B} - \text{Area invaded in year A}}{\text{Area invaded in year A}} \times 100 \text{…………….....}\textbf{Eqn 3.2}$$

$$\text{Invasion rate (\%/yr)} = \left(\frac{\text{Area invaded in year B} - \text{Area invaded in year A}}{\text{Area invaded in Year A}} \times 100\right) \div 30 \text{……..}\textbf{Eqn 3.3}$$

The 2017 spatial extent of bracken fern was assessed in terms of distribution of the species at different distances from the Chelinda pine plantation and linear features (roads and rivers). Feature buffers (Table 3.3) were created using the fixed distance buffer function from the vector geoprocessing tools in QGIS (Figure 3.6) as outlined by Treglia, (2016).

Table 3:Buffer features used as reference points for assessing bracken fern spatial distribution on the Nyika plateau.

Buffer ID	**Linear features**				**Chelinda Pine Plantation**	
	Riverine		**Road**			
	Distance (m)	Area (ha)	Distance (m)	Area (ha)	Radius (m)	Area (ha)
1	100	41000	100	3000	1000	2000
2	250	6800	250	9000	2500	5000
3	500	114000	500	13000	5000	14000
4			750	18000	7500	27000
5			1000	24000	10000	44000

NB: All area values are rounded to the nearest thousand. Streams and rivers across the entire plateau where used, whereas roads within 10Km radius from the plantation were sampled for the analysis.

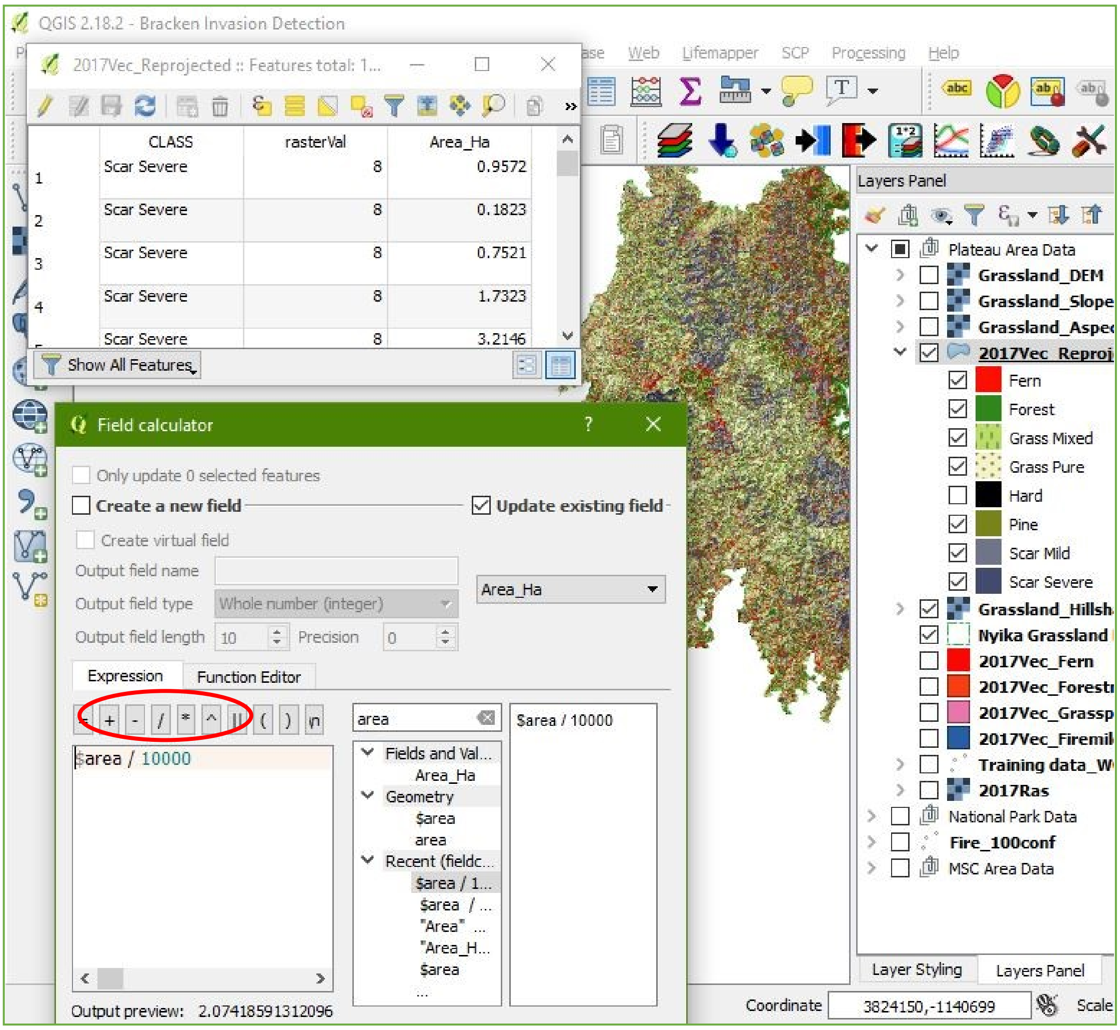

Figure 4: Function (in red circle) used to calculate area covered by pixel-objects in the classified images.

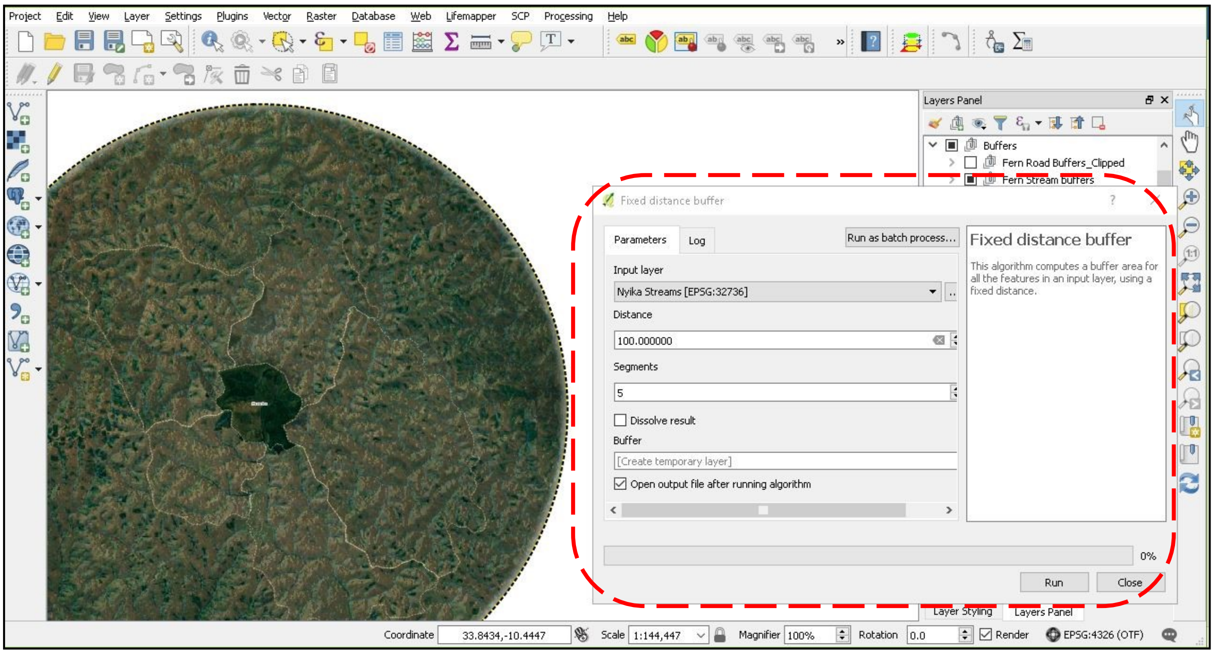

Figure 5: Fixed distance buffer menu (highlighted in red) used to create buffers for spatial analysis of bracken fern distribution on the Nyika plateau in QGIS.

2.4 Assessment of the effect of Bracken fern invasion on Plant Diversity on the Nyika plateau

Figure 3.3 illustrates the harmonized methodology employed in assessing the effect of bracken fern invasion on plant diversity in Nyika National Park. The objective was largely achieved using vegetation ecology techniques.

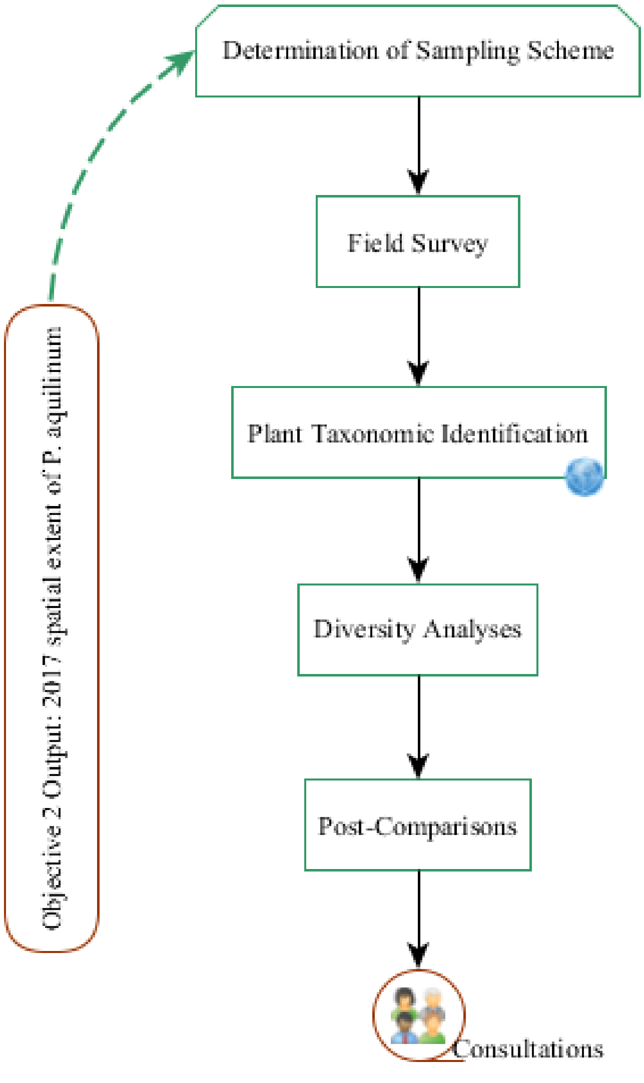

Figure 6: Overview of methodology for determining the spatial-temporal distribution and current coverage of bracken fern on the grassland plateau.

2.4.1 Determination of Sampling Scheme

Determination of the area from which to compare plant diversity between bracken fern invaded and uninvaded areas was based on the output obtained from the 2017 assessment of bracken fern extent. Accessibility of the areas in question was also factored in during selection of areas where to lay plots for diversity assessments. Thus, Figure 3.8 presents the segmentation of NNP, whilst Figure 3.9 shows where plots were laid in the study sampling area. This area was considered sufficient in representing both grassland and bracken fern invaded areas on the plateau. Simple random sampling was used in laying of plots from which to assess plant diversity.

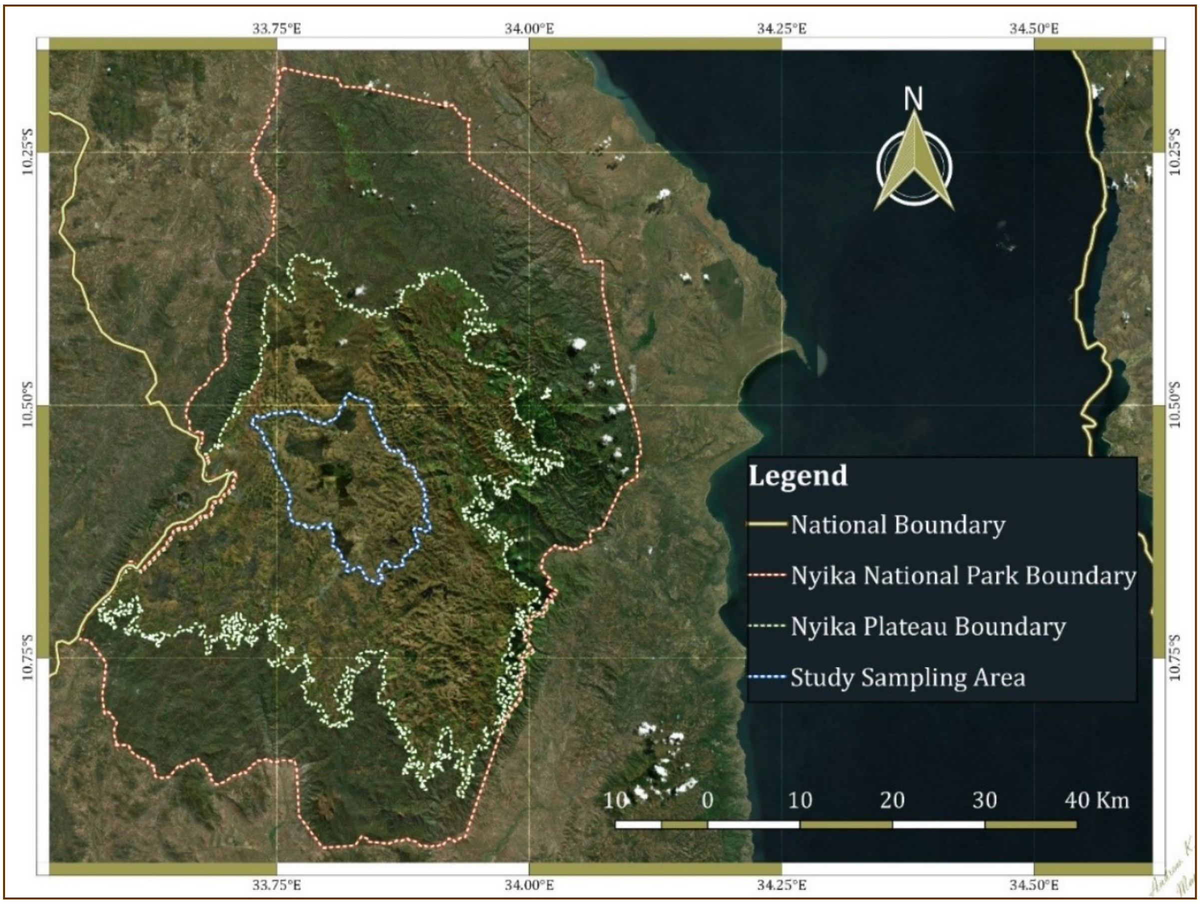

Figure 7: Area used for laying sampling plots on the grassland plateau within Nyika National Park.

2.4.2 Field Survey (Plant Inventory and Taxonomic Identification)

Sample rarefaction and/or species accumulation curves as described in Colwell *et al.,* (2004) were used to determine the optimum number of sampling plots for collecting data on plant diversity in the sampling area (see Figure 3.10). Following the steps described in Hill *et al.,* (2005), a plot of $100m^2$ was set up containing 3 quadrats ($1m^3$ each) laid diagonally within the plot. Plots were laid where the dominant vegetation (grass or bracken fern) covered more than $2500m^2$. Thus, 40 plots evenly distributed in bracken fern invaded and non-invaded areas were laid on the grassland plateau during the survey. Species taxon were identified in the field using the Southern Africa Botanical Diversity Network (SABONET) checklist for plants on the Nyika plateau (Burrows & Willis, 2005). Where species were difficult to differentiate in the field, specimen were verified further using the at the Mzuzu National Herbarium and Botanic Gardens.

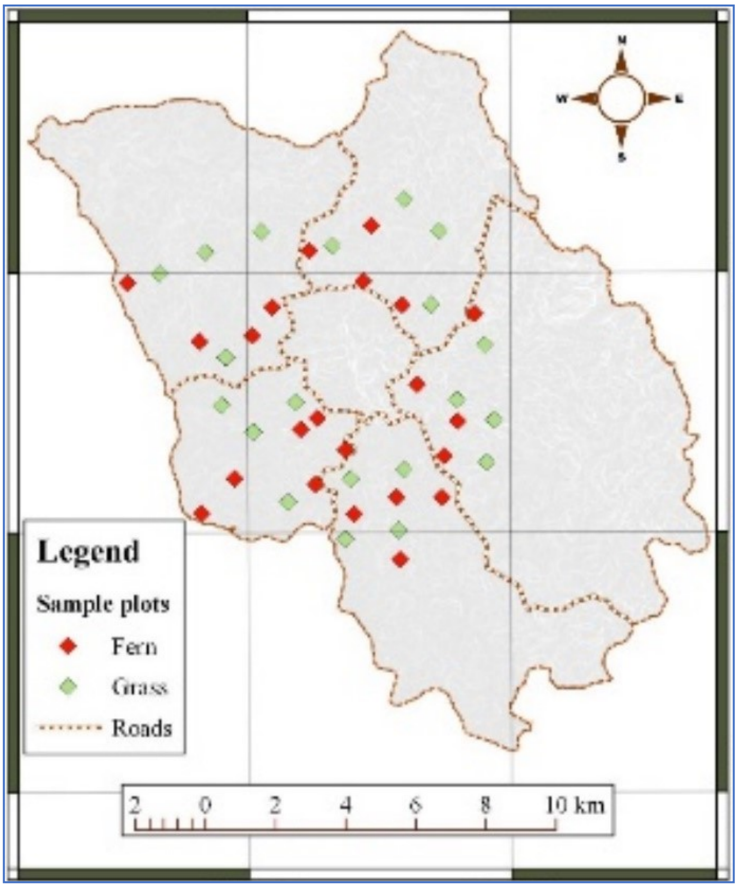

Figure 8: Distribution of sampling plots in the study sampling area.

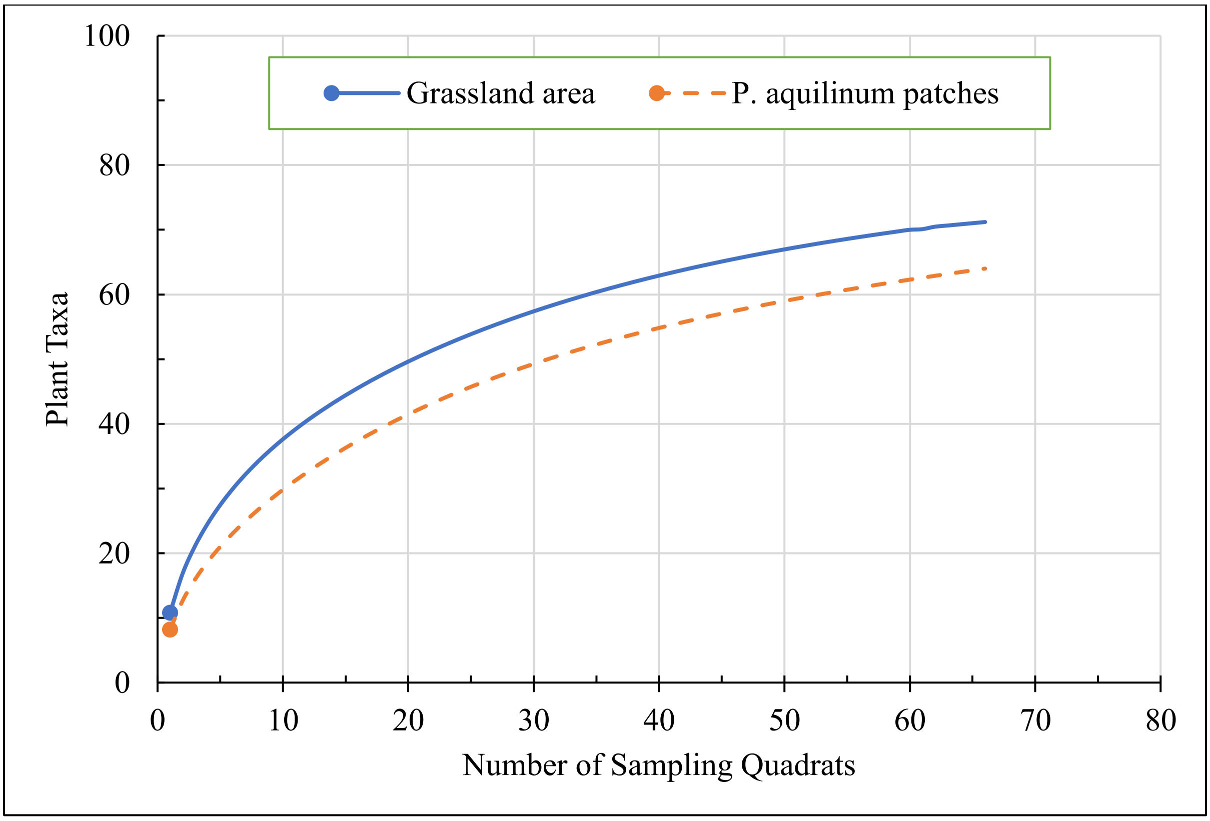

Figure 9: Species accumulation curves for plots in invaded and non-invaded areas.

2.4.3 Diversity Analyses

Species counts, frequencies, abundance and densities were calculated using the statistics functions in Microsoft Office Excel 2016. These parameters were then used to calculate the Simpsons Index (D), Simpsons Index of Diversity [1-D], Shannon Diversity Index [H] and Shannon's Equitability/Evenness [E_H] using the diversity indices function in Paleontological Statistics version 3 (PAST-v3.0). The indices were calculated using the formulae below as outlined in Magurran (1988) and Morris *et al.,* (2014).

$$Shannon\ Index\ (H) = -\left\{\sum_i \left(\frac{n_i}{n}\right) In\left(\frac{n_i}{n}\right)\right\}$$ ………………..**Eqn 3.3**

Where $\boldsymbol{H}$ ranges from 1 (low diversity) to 4.5 (high diversity), $\boldsymbol{n_i/n}$ denotes the proportion of a species ($\boldsymbol{n_i}$) to the total number of species ($\boldsymbol{n}$) in the community, and ***In*** denotes the natural logarithm.

$$Equitability\ (E_H) = {}^{H}/_{In(n)}$$ ………………..**Eqn 3.4**

Where $\boldsymbol{E_H}$ ranges from 0 (uneven) to 1 (complete evenness), $\boldsymbol{H}$ is the Shannon index and ***In(n)*** is the natural logarithm of all species in the community.

$$Simpson's\ Index\ (D) = \sum_i \left(\frac{n_i}{n}\right)^2$$ ………………..**Eqn 3.5**

Where $\boldsymbol{D}$ ranges from 0 (infinitely high diversity) to 1 (no diversity) and $\boldsymbol{n_i/n}$ denotes the proportion of a species ($\boldsymbol{n_i}$) to the total number of species ($\boldsymbol{n}$) in the community.

$$Simpson's\ Index\ of\ Diversity\ (1 - D) = 1 - \left\{\sum_i \left(\frac{n_i}{n}\right)^2\right\}$$ ………………..**Eqn 3.6**

To make the Simpson's index more logical (seeing as the index is counter-intuitive), the index was subtracted from 1 so that values closer to 1 represent higher diversity and those close to 0 represent low diversity as illustrated in Equation 3.6.

2.4.4 Post-Diversity Comparisons

The effective number of species was calculated as illustrated in Equations 3.7 and 3.8 to allow comparison of species richness as outlined in **Hammer *et al.,* (2001)** and explained in **Jost (2006)**. Additionally, Sorensen's Coefficient (*CC*) and Jaccard's Index (*J*) were also calculated to compare the extent of similarity in specific types of plant taxa between the invaded and uninvaded communities as illustrated in equations 3.9 and 3.10. *CC* and *J* both range from 0 (complete species dissimilarity) to 1 (complete community overlap).

$$Shannon\ Effective\ Number\ of\ Species\ H^{e} = exp\left\{-\sum_i \left(\frac{n_i}{n}\right) In \left(\frac{n_i}{n}\right)\right\}$$ ……**Equation 3.7**

$$Simpson's\ Reciprocal\ Index\ (1/D) = 1 \Big/ \left\{\sum_i \left(\frac{n_i}{n}\right)^2\right\}$$ ……………………………**Equation 3.8**

$$Sorenson's Coefficient\ (CC) = 2C / S1 + S2$$ ………………**Equation 3.9**

Where *C* is the total number of species the two communities have in common, whilst ***S1*** and ***S2*** denote the total number of species found in communities ***1*** and ***2*** respectively.

$$Jaccard's\ Index\ (J) = S_c / S_a + S_b + S_c$$ ………………**Equation 3.10**

Where S_a and **S_b** are the number of species unique to samples or communities ***a*** and ***b*** respectively, and **S_c** is the number of species common to the two samples.

Further comparison of species abundance between the bracken fern dominated plots and grassland plots were carried out using individual rarefaction and SHE analysis curves as recommended by Colwell *et al.,* (2012). These were generated in PAST-v3.0 using the diversity analysis function. Additionally, Students T-test was afterwards run in Palaeontological Statistics version 3 (PAST-v3.0) to determine whether differences in diversity between the bracken fern invaded and uninvaded grassland plots was significantly different or not at the 95% confidence level.

2.5 Comparison of the physical and chemical properties of soils in Bracken fern invaded and non-invaded areas on the Nyika plateau

2.5.1 Soil sampling, preparation and Analyses

Determination of the area from which to lay plots and collect soil samples was adopted from the sampling scheme of sampling plant diversity (cf. Figure 3.9). Soil samples were thus collected from invaded areas (n=12) and non-invaded areas (n=12) on the grassland plateau. Within each plot, three soil sampling points along the diagonal of the plot were used to collect soil samples at depths of 20cm and 40cm. A total of 142 soil samples were collected, each weighing approximately 500 grams. The collected samples were stored in labelled plastic bags and transported for further processing and laboratory analysis at the Lunyangwa Research Station. At the research station, soil samples were sorted according to their labels (location and depth) and air dried for three days so as to reduce moisture and allow for easy crushing. Samples were then ground into finer sizes using a pestle and mortar, and sieved using a 2mm sieve mesh. The finely sieved soil samples were then emptied into plastic bottles and stored at room temperature for analysis of physical and chemical parameters. These were used for further analyses of soil physical and chemical properties.

2.5.2 Physical and Chemical Analyses

Soils were analysed for total clay content, sand content, pH, organic carbon (C), organic matter (OM), total mineralizable nitrogen (TN), available Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Cation Exchange Capacity (CEC). Clay and Sand content were determined using procedures outlined in Chilimba (2007) and pH was determined using a pH meter. Total organic carbon was analysed using the Walkley and Black method, from which the Organic matter (OM) was determined. The total mineralizable nitrogen (TN) was obtained as a fraction (5%) of the OM. Available phosphorus was analysed using Mehlick-3 extractant. To determine the rest of the cations, soil samples were transported to Chitedze Research Station where an Atomic Absorption Spectrophotometer (AAS) was used to analyse the samples. CEC was calculated as outlined in Chilimba (2007).

2.5.3 Statistical Analyses

Data were analysed using Paleontological Statistics (PAST) version3.0 software (Hammer, 2016). Students' independent T-test was carried out to compare soil parameters between bracken invaded and non-invaded sites.

3.0 RESULTS & DISCUSSION

This section discusses the findings of the study. The findings for the first and second objectives are combined seeing as they deal with the distribution of bracken invasion, whereas the results for objectives three and four are combined in that they both deal with impacts of the invasion.

3.1 Spatial-temporal distribution of Bracken fern invasion on the Nyika plateau.

The current study set about to establish the current spatial extent and pattern of bracken fern, as well as its temporal distribution in terms of overall change and rate of spread across the plateau over a 30-year period (1986-2016) as in the following subsections.

3.1.1 Spatial distribution of Bracken fern invasion on the Nyika plateau.

In mapping the spatial distribution of bracken fern across the Nyika plateau, the results from this study revealed that the actual coverage of the species detected in the area as of 2017 was 20940.73ha, approximately 14% of the entire grassland plateau in NNP (Table 3.1). The largest land cover proportion was by grasslands (50.63%) followed by fire scars (20.14%), whereas bare ground covered the smallest area (0.86%). No distinct spatial pattern for bracken fern was however noted, seeing as the species was detected almost across the entire plateau as shown in Figure 3.1[1]. This particular finding empirically sustains the observations of Nxumayo (2016) and Kanzunguze (2016) regarding the apparent spread of the species on the grassland plateau in Nyika National Park. Such widespread distribution of bracken fern is also consistent with the observations of several authors described by Robinson *et al.,* (2010) who have made mentioned of the cosmopolitan nature of the species and its adaptability to a wide range of environmental conditions.

Table 4: Proportion of bracken fern and other land cover classes on the grassland plateau in Nyika National Park as of 2017.

Class	Area (ha)	Proportion of plateau (%)
Bracken fern	20940.7	13.57
Grasslands	78145.1	50.63
Forests	22839	14.8
Fire scars	31102.7	20.14
Bare ground	1333.5	0.86

[1] Accuracy assessment error matrix for the image classification is presented in the appendices.

Figure 10: 2017 land cover classification of the Nyika Plateau.

Whilst no overall spatial pattern was conspicuous, the results further revealed that the bracken was concentrated most dense within a 5km radius around the 500ha pine plantation on the grassland plateau (Table 3.2), wherein the species covered approximately 25% (833ha) of the entire 1730.2ha around the plantation. The proportion of bracken fern area declined away from the pine plantation up to 5Km, after which point a 2.4% increase in proportion of bracken fern was detected up to 10Km away from the plantation.

Table 5: Spatial distribution of bracken fern infestation, increase in area infested, area around plantation and proportion at different distances from Chelinda pine plantation in NNP.

Distance from Plantation (Km)	Area of Bracken fern infestation (ha)	Area increment of Bracken fern infestation (ha)	Area around plantation (ha)	Proportion of Bracken fern area (%)
1	433.4		1730.2	25.1
2.5	883.6	+450.1	5331.9	12.5
5	1646	+812.4	14443.3	8.9
7.5	2874.5	+1228.5	27462	9.4
10	4790.7	+1916.3	44382	11.3

NB: Appendix D further illustrates the distribution highlighted in this table.

Furthermore, results on the spatial pattern also revealed that bracken fern was closely distributed along linear features (roads and riverine features). As outlined in Tables 3.3 and 3.4, it was shown that most bracken occurred densely within 100m and 150m buffer areas alongside roads and riverine systems respectively. The largest proportion of bracken fern along roads was detected within the 100-meter and the 500-meter road distances, with the proportion of bracken infestation declining beyond 500m (Table 3.3). As for the rivers and streams, a larger proportion of bracken fern area of infestation (7.8%) was detected between the 150m and 250m riverine buffers with less bracken detected beyond the 250m buffer distance (Table 3.4).

Table 6: Spatial distribution of bracken fern area covered, increase in area, area of buffer around roads and proportion at different distances from the roads in NNP

Distance from road (-m-)	Area of Bracken fern infestation (ha)	Area Increment of Bracken fern infestation (ha)	Area of road buffer (ha)	Proportion of Bracken fern area (%)
100	454.6		3010.8	15.1
250	947.1	+492.6	8871.7	8.4
500	1554.6	+607.5	12828.2	15.4
750	2013.9	+459.3	18153.5	8.6
1000	2540.8	+526.9	24427.5	8.4

NB: Appendix E illustrates the distribution highlighted in this table.

Table 7: Spatial distribution of bracken fern area covered, increase in area, area of buffer around streams and proportion at different distances from the streams in NNP.

Distance from stream (-m-)	Area of Bracken fern infestation (ha)	Area Increment of Bracken fern infestation (ha)	Area of stream buffer (ha)	Proportion of Bracken fern infested area (%)
150	1680.5		41286.8	4.1
250	3736.4	+2055.9	67695.1	7.8
500	4392.5	+656.	113554.3	1.4

Ershova (2010) made mention of an association between bracken fern and pine species in Siberia, in agreement with observations made by Marrs and Watt (2006) regarding the same association between bracken fern and pines in the temperate regions (Great Britain in particular). In these studies, bracken fern patches were denser close to pine stands than further away. Furthermore, Marrs and Watt (2006) also highlighted the consistent occurrence of bracken fern along linear features such as hedgerows, roadsides, verges, tracks and woodland edges in the United Kingdom, complementing earlier findings on bracken fern invasion in New Zealand by Taylor (1985).

Whilst no distinctive spatial pattern for bracken fern across the Nyika plateau was conspicuous in this study (Figure 3.1), the increased density of the species in close proximity to the Chelinda pine plantation and along linear features demonstrated in this study provides a starting point for investigations into the reasons for the current distribution of the species in the park. To complement such enquiries, it may be equally necessary to establish the distribution pattern of the species from other important spatial features such as forest areas on the edges of the grassland plateau, as well as the common tourist attraction sites in the park such as the Juniper forest South of Chelinda plantation and Nganda peak in the north. In light of such an invasion pattern associated with linear features, management of Nyika National Park may have to carefully consider their plans on road construction and maintenance activities in the national park. Considering such activities as ecological disturbances, these could be perhaps paving the way for further invasion and establishment of bracken fern within the national park.

Regarding enquiries into factors promoting spread, one factor that could be influencing the current distribution of bracken fern on the Nyika plateau is the widespread and apparently frequent occurrence of both controlled and wild fires across the Nyika plateau in the protected area (Johnson, 2017). Already in this study, approximately 20% (31102.7ha) of the grassland plateau was revealed to have been burnt by fires during the assessment (Figure 3.1 and Table 3.1), an area which may have been occupied (before or afterwards) by the species bracken fern. This possibility of fires influencing the distribution of bracken fern stems from the well documented adaptive behaviour of invasive ferns after fires (Walker & Sharpe, 2010), especially the rapid post-establishment behaviour of bracken fern according to Gliessman, (1978), Atkinson, (2004) and Thomas *et al*., (2014). A closer look by management at the fire regime would therefore be considered very critical in order to monitor bracken fern invasion.

3.1.2 Temporal distribution of Bracken fern invasion on the Nyika plateau.

In assessing the temporal distribution of bracken fern on the Nyika plateau, the results revealed that bracken fern coverage has increased between 1986 and 2016. As demonstrated in Table 4.6, net increments in bracken fern coverage of 2573.1ha and 19919.4ha detected over the sampled area and entire plateau expanse respectively were revealed. Both scenarios (sampled area and entire plateau) reflect an average 56.9% increment in the area invaded by bracken fern. Furthermore, Table 4.7 reveals a larger proportion of the grassland plateau was invaded by bracken fern in 2016 (20.2%) than in 1986 (9.1%), equivalent to an invasion rate of approximately 4.1% per year (i.e. 663.9ha/yr) between 1986 and 2016. Figure 4.2 illustrates the increase as a change – map of bracken fern invasion between 1986 and 2016.

Table 8: Percentage change in area of bracken fern invasion on the Nyika plateau between 1896 and 2016.

Site on the Nyika plateau	Area in 1986 (ha)	Area in 2016 (ha)	Area Change from 1986 to 2016 (ha)	Percentage Change (%)
Sampled area	1788.79	4361.93	+2573.13	+143.8
Entire plateau	16344.61	36263.98	+19919.38	+121.9

Table 3.6: Area invaded by bracken fern expressed as a proportion of the entire Nyika plateau between 1986 and 2016.

Year	Plateau area invaded with Bracken fern (ha)	Proportion of plateau invaded with Bracken fern (%)	Proportion increment of invaded area (%)
1986	16344.61	9.08	-
2001	30693.97	17.05	+7.97
2016	36263.98	20.15	+3.1

NB: Annual rate of invasion between 1986 and 2016 is 4.064%, approximately 663.9ha per year.

These findings are consistent with several studies elsewhere in revealing an inevitable increase in bracken fern coverage over time. For instance, Curatola-Fernandez *et al.*, (2015) reported a 4.41% annual rate of increase in bracken fern coverage in Southern Ecuador over a 14-year period (1987-2001), whilst Schneider and Fernando (2010) reported a 9.09% rate of increase in the coverage of bracken fern over a 15-year period (1989-2005) in different cultivation systems of Southern Yucatan (Mexico). Furthermore, whilst McAlpine (2014) reported a relatively low annual increment 0.98% for the species over a 35-year period (1966-2005) in the Peak District National Park (United Kingdom), Singh (2013) reported much larger rates of approximately 25.6% in 2 years (2009-2011) within the uKhahlamba Drakensberg Park World Heritage Site (South Africa).

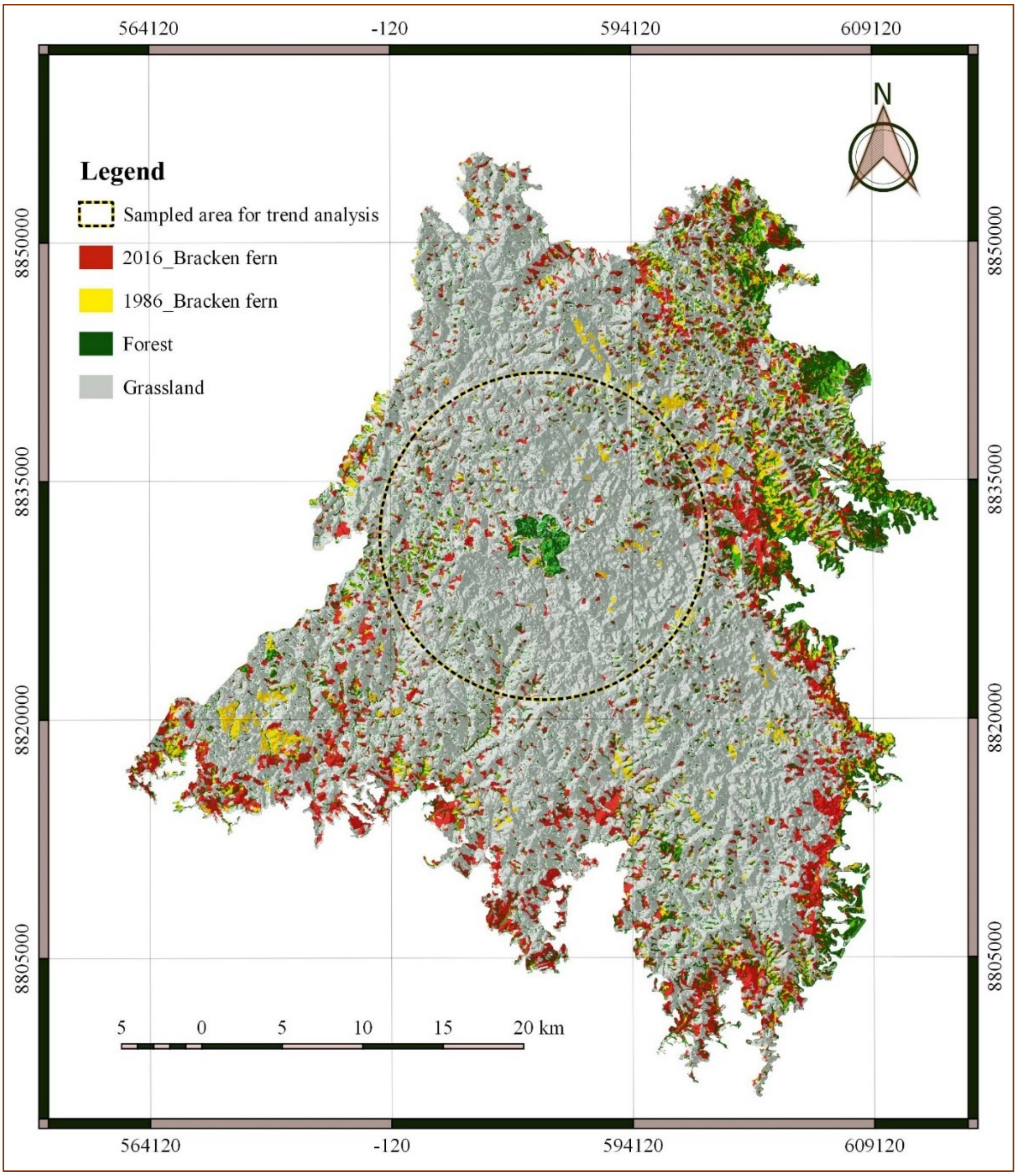

Figure 11: Change map of bracken fern distribution on the Nyika plateau from 1986 to 2016.

Building on the concept of the invasion framework by Blackburn *et al*., (2010) which posits that invasive organisms will inevitably increase their abundance and spread to other areas within a landscape over time, this study strongly posits that further spread and increase in the coverage of the bracken fern on the grassland plateau in Nyika National Park is very likely. Given the 4.06% rate of bracken fern invasion on the Nyika plateau over the past 30 years, the remaining grassland portion of the plateau (109247.8ha) could be invaded within the next 40 years (i.e. by 2055) keeping all other factors influencing its spread constant as illustrated in Figure 4.3. Considering the rates of invasion of the species in other areas heretofore highlighted, total invasion by 2050 could well be a best-case scenario. It may be important for management of Nyika National Park to consider investment, if not particularly on control of the species, at least on further studies to explore and model the distribution of the species in the natinal park so as to zero-in on the pertinence of the invasion. In this line of thought, ecological modelling techniques have been recommended by authors such as Gallien *et al.*, (2010), Kearney *et al.*, (2008) and Phillips *et al.*, (2006) which can go a step further in helping management identify hotspots of bracken fern invasion that could require critical attention within the national park.

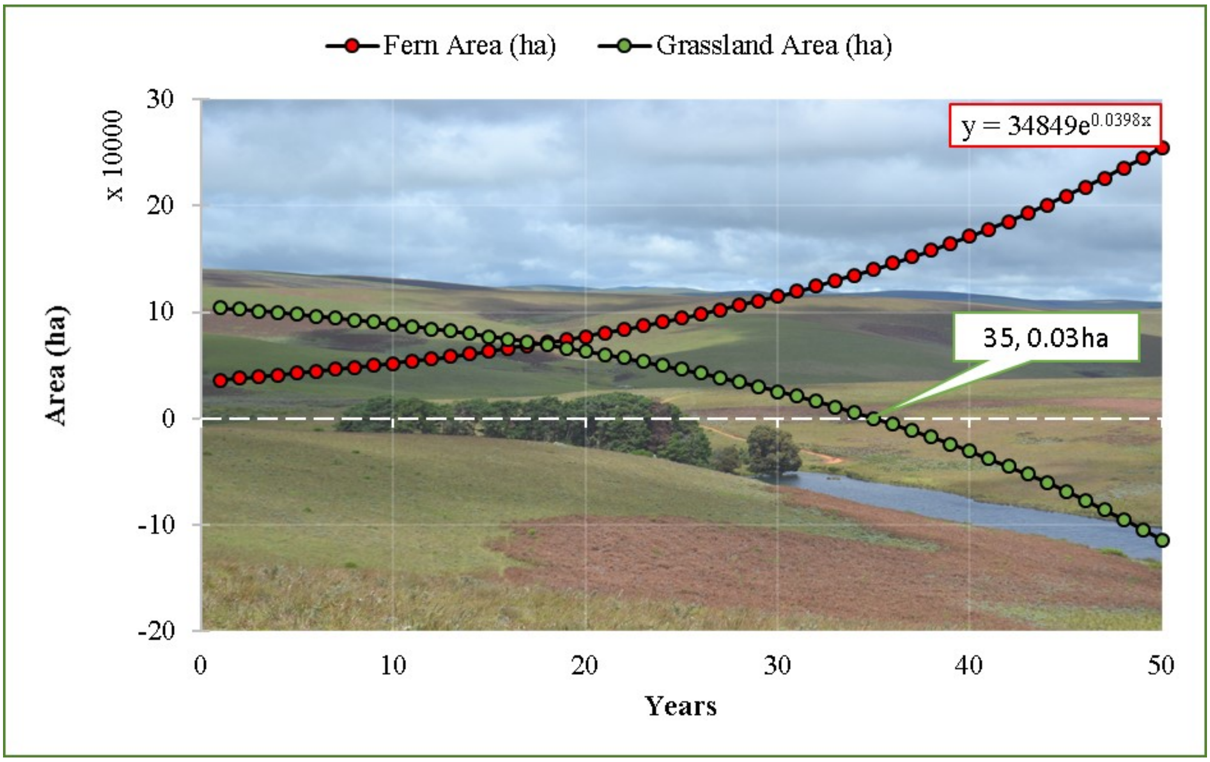

Figure 12: Forecast of change in the area of bracken fern and grasslands on the Nyika plateau.

3.2 Effect of Bracken fern invasion on grassland diversity on the Nyika plateau.

The current study also set about to assess the effect of bracken fern invasion by comparing the current grassland plant diversity, soil physical and chemical properties between bracken fern invaded and non-invaded areas on the Nyika plateau. The results are presented in the following subsections.

3.2.1 Effect of Bracken fern invasion on grassland plant species diversity on the Nyika plateau.

In comparing plant species diversity across the grassland plateau, the results (**Table 3.6**) revealed significantly lower diversity (**p<0.001**) in bracken fern invaded areas (***H=1.93***) than non-invaded grassland areas (***H=2.29***). Similarly, the invaded areas were significantly (**P<0.01**) less even (E_H=***0.723***) than non-invaded areas (E_H=***0.801***). Furthermore, the results revealed about 20% dissimilarity in species richness between bracken invaded and non-invaded plots based on both the Jaccard's index (*J*) and Sorenson's Coefficient (*CC*) similarity indices (*J=0.759, CC=0.863*).

Table 9: Comparison of plant species diversity between bracken fern invaded and non-invaded areas using Shannon's diversity and equitability indices.

Area	**Shannon Index (*H*)**	**Shannon Equitability (E_H)**
Invaded	1.927 ± 0.07	0.723 ± 0.019
Non-invaded	2.289 ± 0.08	0.801 ± 0.015
P-value	0.0015	0.007

NB: Data are means ± standard errors.

Analysis of individual rarefaction curves to compare richness and abundance between bracken invaded and non-invaded areas showed that less than 10 species taxa with individual abundances between 26 and 90 individuals in bracken fern invaded plots (Figure 3.4) as compared to 14 species taxa with individual abundances between 30 and 110 individuals in non-invaded plots (Figure 3.5). Figure 3.6 further illustrates (visually) how bracken fern invaded areas appeared dominated by bracken fern in contrast to other grass species on the grassland plateau. These results generally agree with similar observations of low plant species diversity in areas invaded by bracken fern as reported by McGlone *et al.,* (2005), Marrs and

Watt (2006), and also Schneider and Geoghegan (2006) for bracken invasion in New Zealand, the United Kingdom and Mexico respectively.

According to Robinson *et al.,* (2010), the low diversity and abundance of grassland plant species in bracken invaded areas demonstrated in the rarefaction curves could be a demonstration of allelopathy by the species. This is in agreement with reports from authors such as Engelman & Nyland (2006) as well as Bond *et al.,* (2007) who demonstrated how the rapid regrowth of bracken fronds interferes with the regeneration of other plant species through shading. In addition, the suppressive effect of bracken species on the growth and survival of other grassland vegetation through the release of chemicals from both its rhizomes and fronds in its vicinity was demonstrated in Denmark (Rasmussen, 2003) and Brazil (de Jesus Jatoba *et al.,* 2016). Vetter (2009) also revealed several ways through which bracken fern allelopathically inhibits the growth of other vegetation and therefore results into reduced plant abundances and species richness wherever it invades, complementing earlier findings on the same by Gliessman and Muller, (1977) as well as Pakeman and Marrs, (1991).

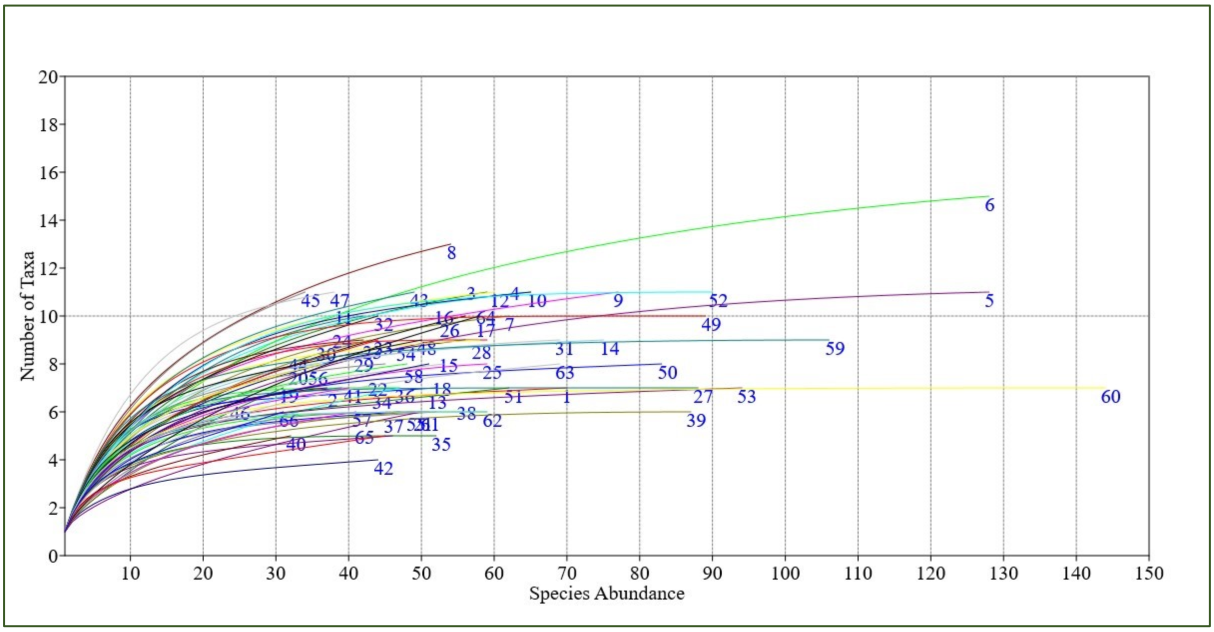

Figure 13: Individual rarefaction curves of bracken fern plots.

Besides allelopathy, authors such as Gliessman, (1978), Marrs and Watt (2006), Walker and Sharpe (2010) as well as Thomas *et al.,* (2014) revealed that ecological disturbances such as fire promote bracken invasion. In addition to the fires that swept across 20.1% of the entire plateau (31,102ha) in 2017 (Table 3.1), Johnson (2017) also reports that wildfires fires are a frequent occurrence on the grassland plateau. Thus, fires may be another factor influencing the spread and dominance of bracken fern on the grassland plateau in Nyika National Park.

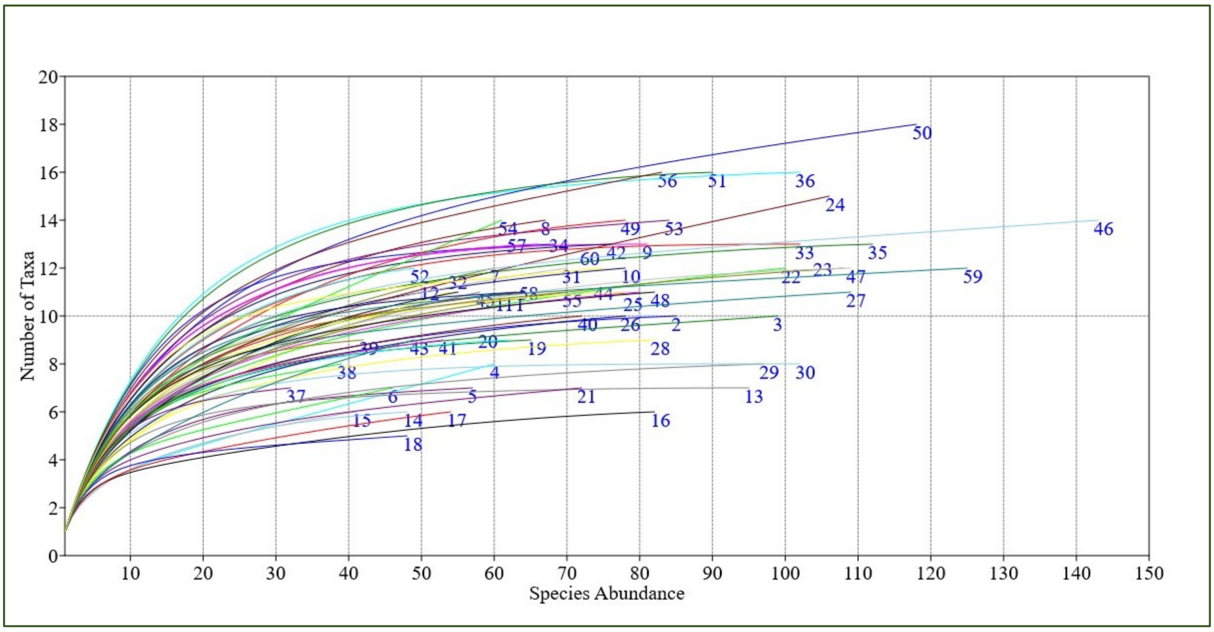

Figure 14: Individual rarefaction curves of grassland plots.

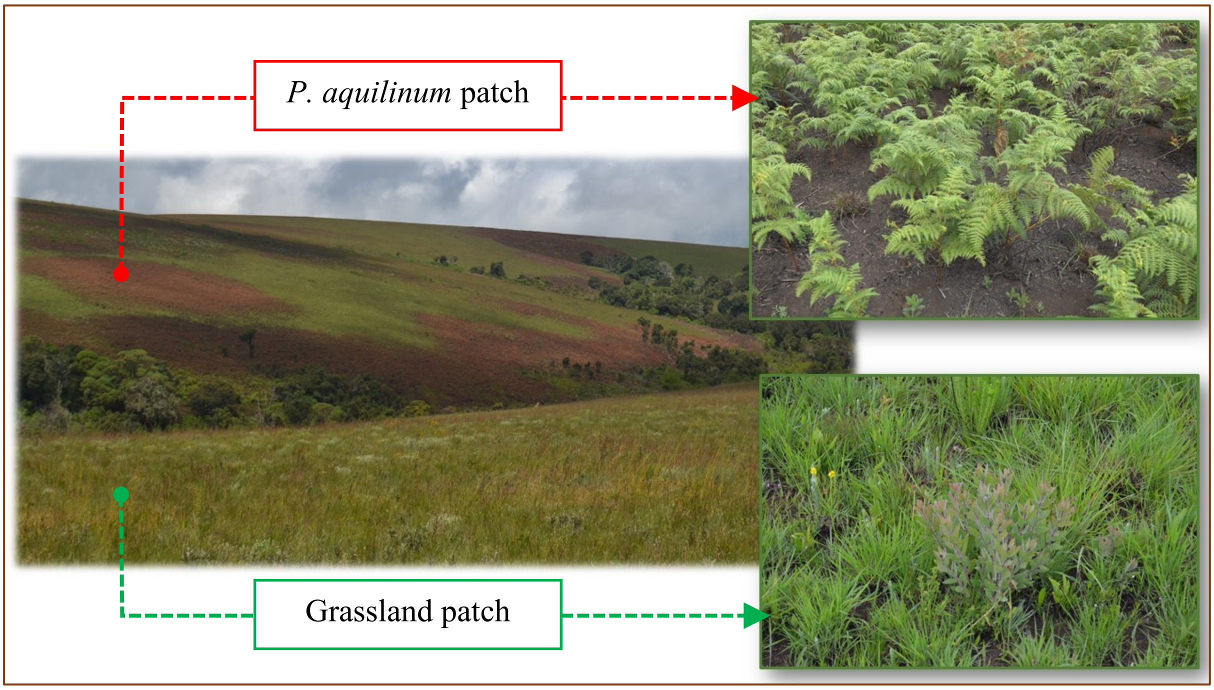

Figure 15: Visual comparison of bracken fern invaded areas (above) and uninvaded areas (below) on the grassland plateau in Nyika National Park.

The findings of the current study substantiate and give credence to the observations of Nxumayo (2016) and Kanzunguze (2016) who described bracken fern as dominating other grassland species wherever it had formed patches on the Nyika grassland plateau. So far, this situation of bracken invasion on the Nyika plateau is similar to that of bracken invasion in the United Kingdom at a point when investigations into its conservation value began to be investigated. At the point, it was revealed that though controlling bracken pread across large landscapes is challenging (Pakeman & Marrs, 1991) and its further spread in the long run is inevitable (Pakeman & Marrs, 1993), mitigation of its negative effects on biodiversity conservation requires prompt development of invasive plant management interventions (Pakeman & Marrs, 1996). A particular point especially echoed in their reviews (Pakeman & Marrs, 1991; 1993; 1996) was that further bracken invasion led to the sure decline in biodiversity and changed succession trajectories from grassland to woodland in bracken invaded communities. Similar concerns have since been raised and reviewed by authors such as Hartig and Beck (2003), Schneider and Geoghegan (2006), and also Stewart *et al.,* (2008) for bracken fern invasions in Southern Ecuador, Mexico and the United Kingdom respectively.

In light of such observations, management of Nyika National Park may need to immediately begin appraising the costs of either developing appropriate management interventions bracken fern invasion in the protected area or neglecting the invasion altogether at the expense of declining plant species diversity and its associated ecological consequences. Mehltreter *et al.* (2010), Simberloff (2013) as well as Genovisi and Monaco (2013) provide holistic reviews to invasive plant species management in protected areas. Furthermore, Radosevich *et al.,* D'Antonio *et al.,* and also Mack and Foster in an earlier review of invasive weed management by Inderjit (2009) recommend different approaches to cost-benefit analysis of invasive plant control interventions. These recommendations could go a long way in informing management of Nyika National Park on feasible ways of addressing bracken fern invasion.

3.2.2 Effect of Bracken fern invasion on soil physical-chemical properties on the Nyika plateau.

In comparing soil physical and chemical properties across the grassland plateau, the results revealed that soils were generally acidic (pH=4.95±0.35), and dominantly clay-rich in bracken fern invaded areas (clay=58.2%, sand=41.8%) than in non-invaded areas (clay=54.2%, sand=45.8%). According to Vetter (2009), pH levels in less than 5.5 are very ideal for bracken fern establishment and colonization. Additionally, results also revealed moderate levels of Organic Matter (1.5 -4%), Soil Carbon (0.88 - 2.35%) and Total Nitrogen (0.12 - 0.2%) in all sampled soils (**Table 3.7**), but these were significantly higher ($P<0.001$) in invaded areas than non-invaded areas.

Table 10: Proportion of total nitrogen, soil carbon and organic matter in soils sampled from invaded and non-invaded areas on the Nyika plateau.

Soil depth (cm)	Plots	Total Nitrogen – N (%)	Soil Carbon – C (%)	Organic Matter – OM (%)
20	Invaded	0.193±0.007 [a]	2.24±0.077 [b]	3.85±0.132 [a]
	Not invaded	0.139±0.009 [b]	1.61±0.463 [a]	2.77±0.174 [b]
40	Invaded	0.162±0.006 [a]	1.88±0.073 [a]	3.24±0.125 [a]
	Not invaded	0.096±0.009 [b]	1.12±0.104 [b]	1.93±0.18 [b]

Data (mean ± standard error of the mean) in columns with different superscripts within a soil depth (i.e. 20cm or 40cm) are significantly different at P<0.001.

Phosphorus (P) levels were generally low in both areas (<18µg/g), but significantly lower (p=0.024) in invaded areas (7.12µg/g) than non-invaded areas (vs 10.66µg/g). Although Magnesium (Mg) levels were generally high in both areas (0.6 - 3cmol/kg), they were also significantly lower (P=0.003) in bracken fern invaded areas (1.77cmol/kg) as compared to the non-invaded areas (2.16cmol/kg). No significant differences in Calcium (Ca) and Potassium (K) levels were revealed between invaded and non-invaded areas, although these were generally high (>0.5cmol/Kg). Additionally, the Cation Exchange Capacity (CEC) of soils from bracken fern invaded areas was generally high in both areas (>30meq/100g), but again significantly lower (P=0.013) in bracken fern invaded areas (31.62meq/100g) than non-invaded areas (36.24meq/100g).

The significant variations in chemical and physical properties of soils in bracken fern-invaded areas as compared to the non-invaded areas on the Nyika plateau reflect the need for careful consideration in development of chemical control interventions. This is mainly because of the slight inconsistency of the current results to findings from other reviews. For instance, the elevated total nitrogen levels in invaded areas was rather contrary to the conclusions and findings of authors such as Marrs and Watt (2006) as well as Griffiths and Filan (2007) for bracken fern invasion in the UK and USA respectively. Furthermore, in the review of fern ecology by Mehltreter et al, (2010), contributors such as Richardson and Walker (2010), Walker and Sharpe (2010) as well as Robinson et al, (2010) seem to suggest consistently reduced soil nutrition in terms of chemical parameters such as nitrogen and phosphorus, in areas invaded by problem ferns (especially bracken fern) which was rather not so consistent with the findings of the current study except in instances as for CEC and P levels (more results on soil analyses in appendices). As such, a lot of changes in the edaphic properties of soils on the Nyika plateau as a consequence of either further bracken fern invasion or any possible control options may remain speculative unless further close monitoring of the soils is consistently carried out alongside plant diversity assessments.

4.0 CONCLUSIONS

Thus far, the study has demonstrated the widespread extent and gradual increase of bracken fern on the grassland plateau in Nyika National Park. Additionally, the remote sensing and geographic information systems approach to detection, mapping and monitoring of the species has proved very effective. Management of the national park could use these findings in appraising the potential cost of different invasive plant management interventions for the species in the national park as well as future monitoring of the invasion.

Secondly, the study has also demonstrated that there are significant differences in plant species diversity as well as selected soil physical and chemical parameters between invaded and non-invaded grassland areas in Nyika National Park. Plant species diversity has particularly been revealed to be lower in invaded areas, whilst the results for soil analysis are very variable. Management of Nyika National Park may seriously need to consider careful monitoring of the changes in the edaphic properties of the grassland plateau (and its associated plant species diversity) in light of further bracken fern invasion or attempted control initiatives.

5.0 RECOMMENDATIONS AND FURTHER RESEARCH

The current study has empirically demonstrated that bracken fern is associated with reduced plant diversity and abundance. One limitation to this finding however, was that it did not highlight the specific taxa that are excluded from bracken fern invaded plots. It is recommended that further work be carried out to monitor plant diversity and abundance in relation to bracken fern invasion on the grassland plateau in NNP, with a focus on identifying the composition (or type) of affected grassland plant species.

The current study also revealed an annual rate of increase of in bracken fern coverage over the plateau of 4.06% (663.9 hectares per year) between 1986 and 2016. A limitation to the use of this result is that it assumes all factors that could influence further spread in the invaded area to be constant. Other studies reveal that there could be more factors at play influencing the spread of bracken fern on the plateau, amongst which is fire. This study thus recommends thorough investigation into the role of fire in influencing the temporal and spatial distribution of bracken fern invasion in Nyika National Park, seeing as fires are reported as an increasing concern in the protected area.

The risk of consequent loss in plant diversity with further bracken fern invasion on the Nyika plateau was also demonstrated in this study. At a 4.06% rate of increase, the remaining uninvaded grassland plateau is projected to have been dominated by bracken fern within the next 40 years if left unaddressed. It is therefore recommended that cost-benefit analyses of different control options for managing the invasion should be promptly carried out. This can also be followed up with actual experimentation of different control options in selected localized areas across the plateau.

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7.0 APPENDICES

Appendix A: Highlights from the study.

1: Surveying bracken fern patches on the Nyika plateau.

2: Collection of soil samples in bracken fern invaded areas.

3: Collecting data on bracken fern density, frond height and rhizome depth.

4: Plant species diversity inventory in pine dominated area on the plateau.

5: With PPF colleagues at their GIS lab in Stellenbosch (SA) for remote sensing analyses.

6: Soil analyses at Lunyangwa research station.

APPENDIX B: ACCURACY ASSESSMENT MATRIX FOR OBJECTIVE ONE

Table 11: Error matrix for 2017 support vector machine image classification.

Class	Fern	Forest	Grass Mixed	Grass Pure	Hard	Pine	Scar Mild	Scar Severe	**TOTALS**	**Producers Accuracy (%)**	**Errors of Omission (%)**
Fern	**40,858**	0	0	0	0	0	0	0	40,858	100	0
Forest	0	**71,247**	0	0	0	0	0	0	71,247	100	0
Grass Mixed	0	0	**355,348**	13418*	0	15*	0	0	368,781	96.4	3.6
Grass Pure	0	0	0	**281,584**	7*	0	0	0	281,591	99.997	0.003
Hard	0	0	0	56	**11,081**	0	0	0	11,137	99.5	0.5
Pine	0	0	0	0	0	**113,631**	0	0	113,631	100	0
Scar Mild	0	0	43,164*	0	0	0	**106,823**	0	149,987	71.2	28.8
Scar Severe	0	0	0	0	0	0	0	**49,060**	49,060	100	0
TOTALS	40,858	71,247	398,512	295,058	11,088	113,646	106,823	49,060	1,086,290		
Consumers Accuracy (%)	100	100	89.2	95.4	99.9	99.98	100	100		**Overall Accuracy: 94.78%**	
Errors of Commission (%)	0	0	10.8	4.6	0.1	0.01	0	0		**Kappa (Kc): 0.933**	

*All values with asterisk are inaccuracies obtained from the classification. Numbers in red represent misclassified pixel-objects whilst numbers in blue represent correct ones

APPENDIX C: SOIL PHYSICAL AND CHEMICAL ANALYSIS RESULTS

A. Comparison of soil physical and chemical parameters between soil samples obtained at 20cm and 40cm depths within (1) invaded and (2) non-invaded grassland plots. The soil pH for all soil samples was between 4.6 and 5.3.

Table 12: Soil physical parameters from *P. aquilinum* (bracken fern) and grassland plots

Sampling area	**Soil depth** (cm)	**Total Nitrogen - N** (%)	**Soil Carbon - C** (%)	**Organic Matter - OM** (%)	**Sand content** (%)	**Clay content** (%)
Fern	20	0.19±0.037 [a]	2.24±0.434 [a]	3.9±0.75 [a]	42.2±5.57	57.8±5.57
	40	0.16±0.035 [b]	1.88±0.41 [b]	3.2±0.71 [b]	41.4±6.78	58.6±6.78
Grassland	20	0.14±0.039 [a]	1.61±0.462 [a]	2.8±0.8 [a]	46.7±6.19	53.3±6.19
	40	0.09±0.041 [b]	1.12±0.477 [b]	1.9±0.82 [b]	44.9±5.36	55.1±5.36

Data (mean ± standard deviation) in columns with different superscripts within a sampling area (i.e. fern or grassland) are significantly different at P<0.01.

Table 13: Soil chemical parameters from *P. aquilinum* (bracken fern) and grassland plots

Sampling area	**Soil depth** (cm)	**Cation Exchange Capacity - CEC** (meq/100g)	***Phosphorus - P** (ppm)	**Calcium - Ca** (ppm)	**Potassium - K** (ppm)	**Magnesium - Mg** (ppm)
Fern	20	31.6±6.63	9.3±9.89	3.5±1.49	10.4±1.75	17.7±4.87
	40	33.1±5.58	6.3±4.39	3.9±1.37	10.5±1.37	18.7±4.05
Grassland	20	36.8±6.75	12.5±14.61	3.9±1.74	10.9±1.74	22.0±4.51
	40	35.7±5.76	8.8±19.34	3.7±1.39	10.7±1.39	21.2±3.96

Data are (mean ± standard error). Phosphorus readings from samples in both plots displayed very large levels of variation at both soil depths.

Table 14: Phosphorus (P) levels from P. aquilinum and grassland plots

Sampling area	**Soil depth** (cm)	**N**	**Mean Phosphorus content - P** (ppm)	**Variance**	**Standard deviation**	**Standard error of the mean**
Fern	20	64	9.263	97.871	9.89	1.75
	40	64	6.325	19.171	4.39	0.78
Grassland	20	42	12.49	213.43	14.61	3.19
	40	42	8.829	373.63	19.34	4.22

B. Comparison of soil physical parameters between soil samples obtained from grassland plots invaded by *Pteridium aquilinum* (Bracken fern) and grassland plots not invaded by *P. aquilinum* at 20cm and 40cm depths.

All physical parameters of soils collected at both 20cm and 40cm depths were significantly different at P<0.001 between grassland plots invaded by *P. aquilinum* and those plots not invaded by the species.

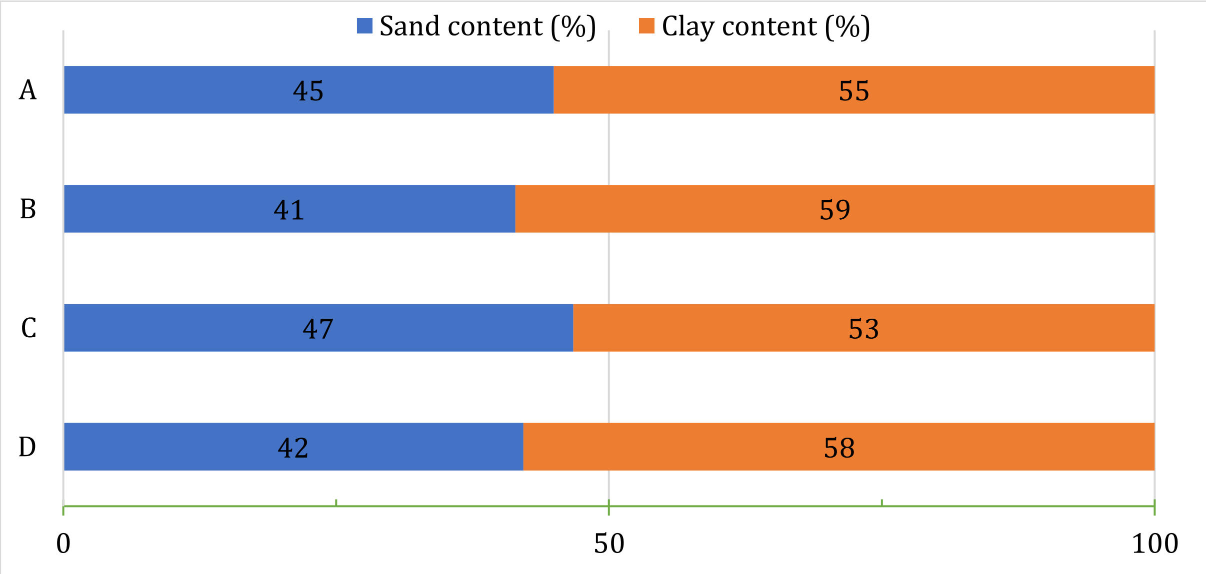


Figure 16: Clay and Sand content in plots not invaded with *P. aquilinum* at 40cm soil depth (A) and 20cm soil depth (C), and plots invaded with *P. aquilinum* at 40cm soil depth (B) and 20cm soil depth (D) on the grassland plateau.

C. Comparison of soil chemical parameters between soil samples obtained from grassland plots invaded by *Pteridium aquilinum* (Bracken fern) and grassland plots not invaded by *P. aquilinum* at 20cm and 40cm depths.

Table 15: Chemical parameters significantly different at P<0.01 between *P. aquilinum* invaded and uninvaded plots at different depths.

PLOTS	**Cation Exchange Capacity** (meq/100g)		**Magnesium** (ppm)	
	20cm depth	40cm depth	20cm depth	40cm depth
Invaded with fern	31.6 [b]	33.1	17.659 [b]	18.675 [b]
Not invaded with fern	36.8 [a]	35.7	22.014 [a]	21.19 [a]

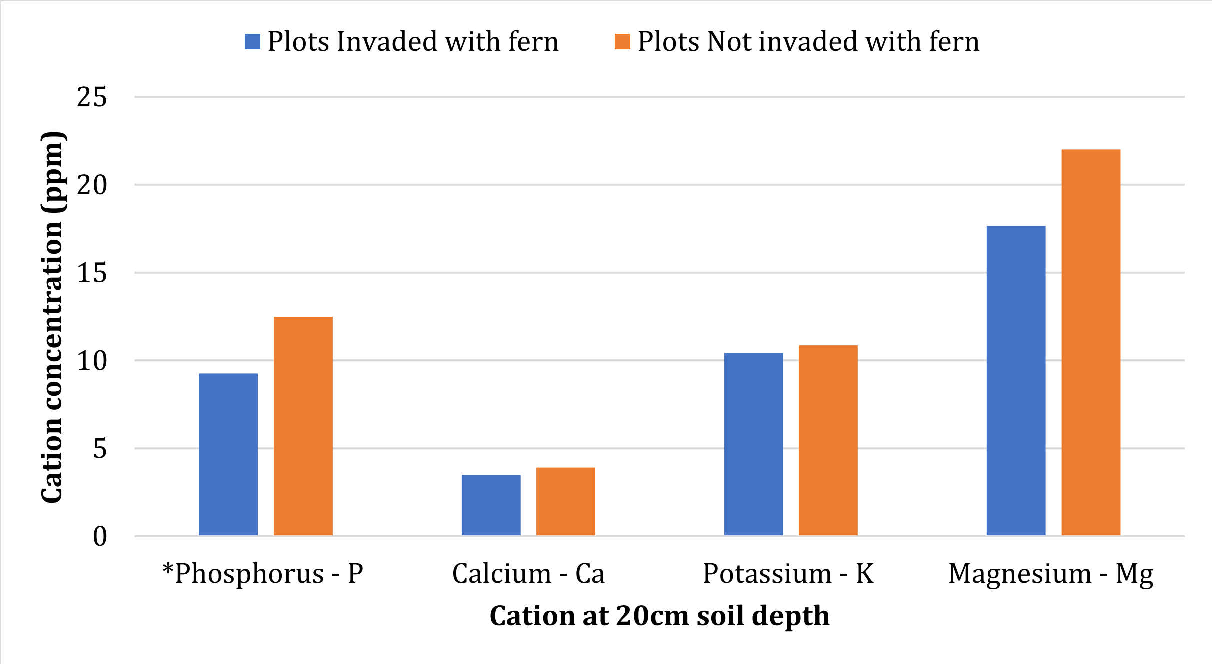


Figure 17: Cation concentrations at 20cm soil depth.

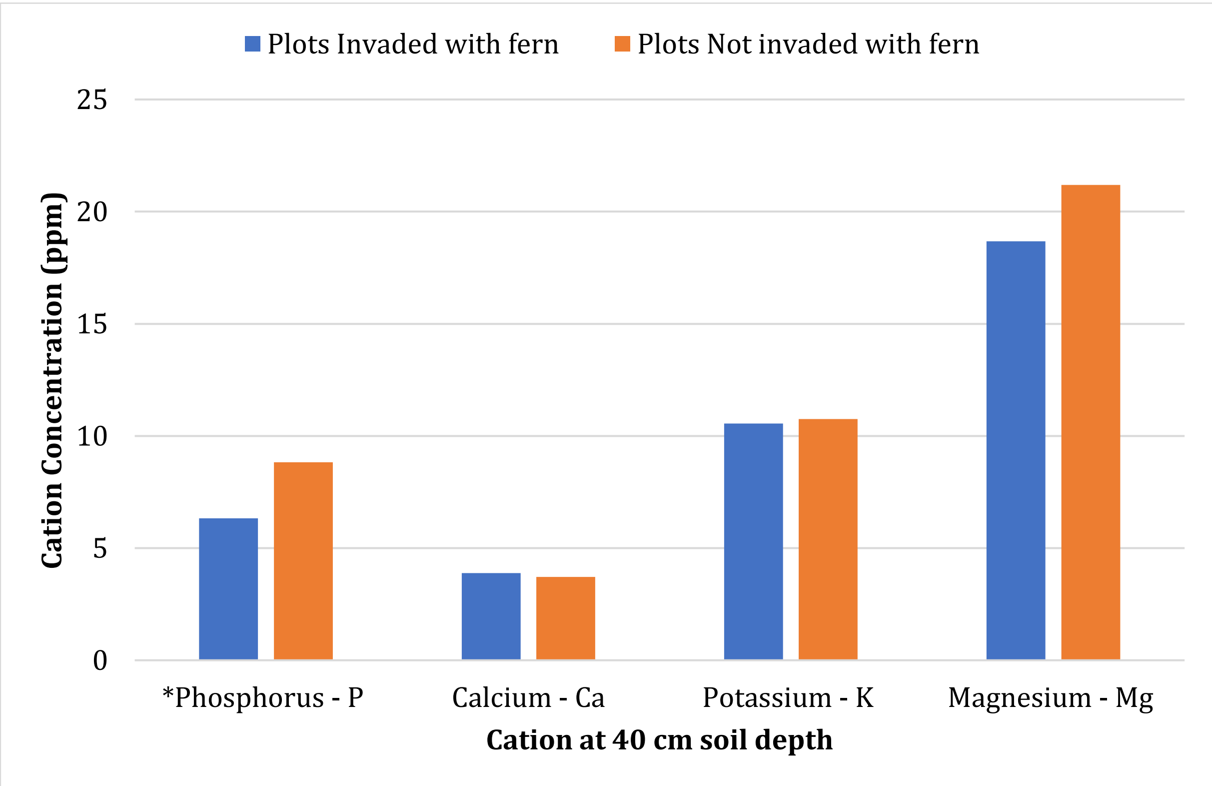
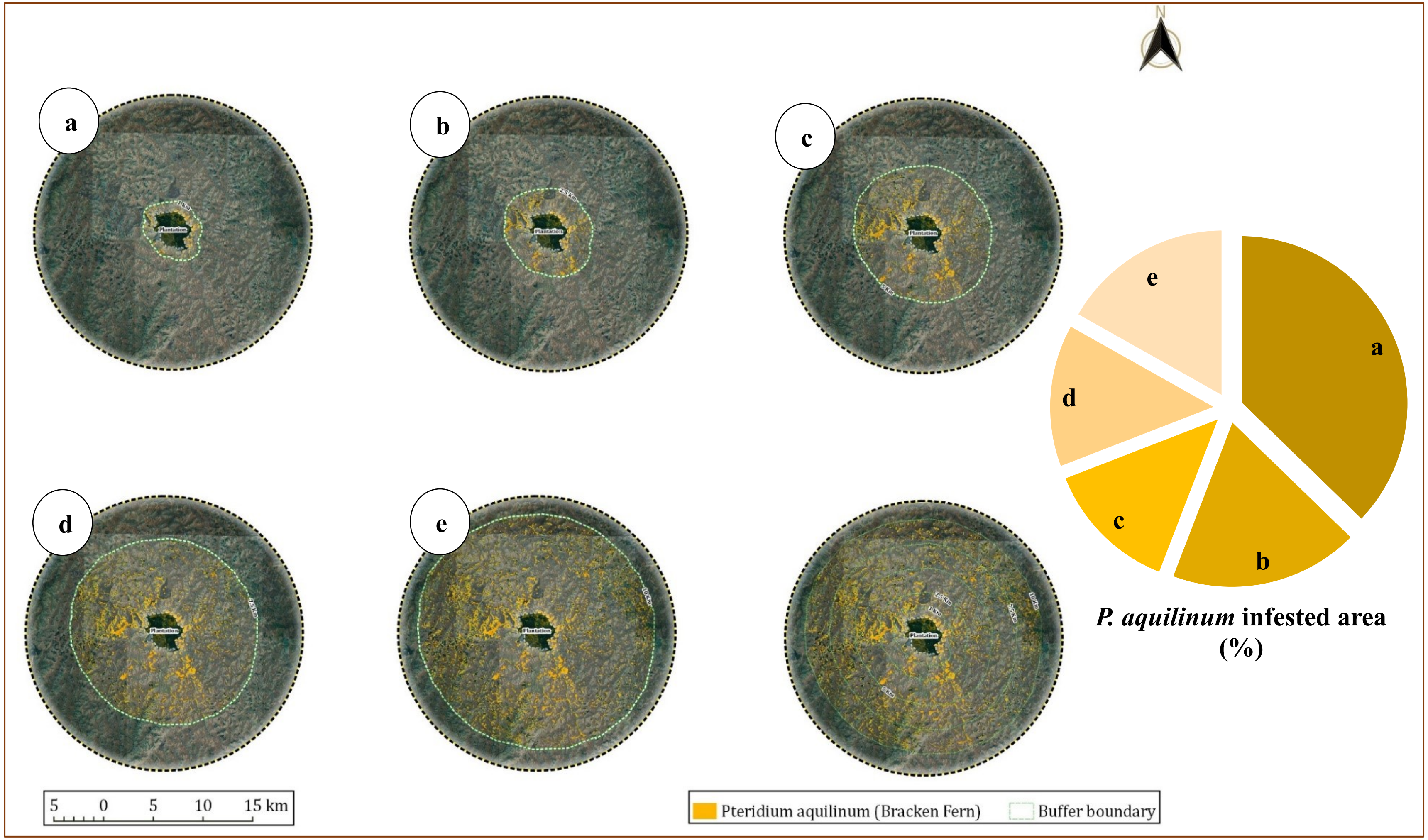
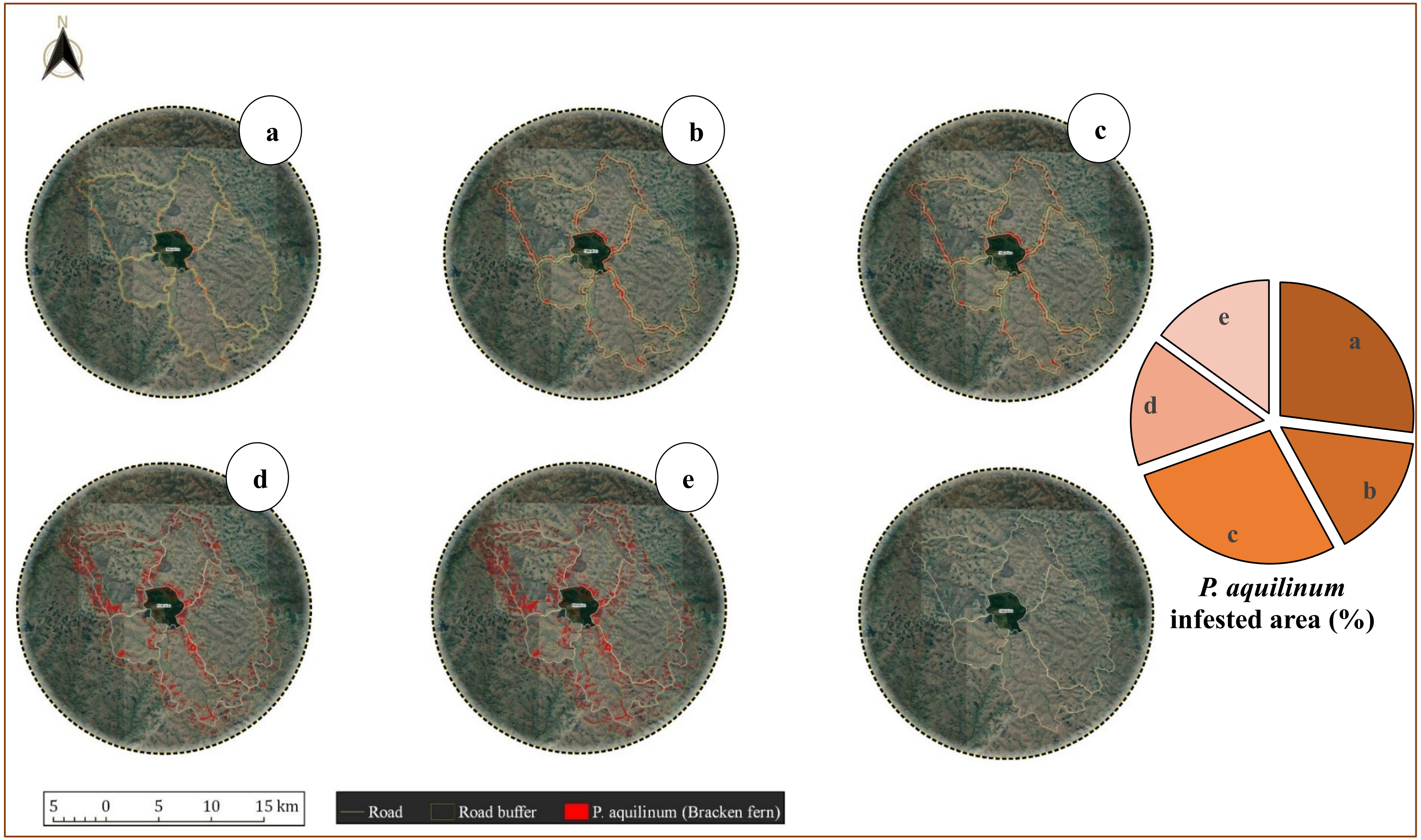


Figure 18: Cation concentrations at 40cm soil depth.

Appendix D: Spatial extent of *P. aquilinum* on the central plateau at (a) 1Km, (b) 2.5Km, (c) 5Km, (d) 7.5Km and (e) 10Km distances from the Chelinda pine plantation.



Appendix E: Spatial extent of *P. aquilinum* on the central plateau at (a) 100m, (b) 250m, (c) 500m, (d) 750m and (e) 1000m distances from the roads around Chelinda pine plantation.



Appendix F: Coordinates used in determining the 2017 spatial extent of *P. aquilinum*. (Coordinates were collected in UTM zone 36 south using the world geodetic system of 1984)

Category	Id	x	y
Fern patch	1	587384	8827418
Fern patch	2	587148	8827451
Fern patch	3	587385	8828186
Fern patch	4	587068	8828635
Fern patch	5	587011	8828919
Fern patch	6	587881	8828845
Fern patch	7	587551	8828892
Fern patch	8	589334	8828726
Fern patch	9	589875	8827029
Fern patch	10	589859	8826865
Fern patch	11	590295	8826565
Fern patch	12	590355	8826730
Fern patch	13	591390	8826954
Fern patch	14	591448	8827211
Fern patch	15	591270	8827165
Fern patch	16	590804	8828320
Fern patch	17	589965	8829580
Fern patch	18	590236	8825067
Fern patch	19	589486	8824945
Fern patch	20	589785	8823730
Fern patch	21	591493	8829309
Fern patch	22	584268	8832221
Fern patch	23	584458	8832296
Fern patch	24	585466	8832715
Fern patch	25	584268	8831006
Fern patch	26	583216	8831380
Fern patch	27	586394	8831832
Fern patch	28	590505	8831321
Fern patch	29	590670	8831306
Fern patch	30	590640	8831727
Fern patch	31	590458	8831604
Fern patch	32	589800	8832175
Fern patch	33	589499	8832746
Fern patch	34	592215	8831980
Fern patch	35	591990	8832384
Fern patch	36	592531	8832310
Fern patch	37	592380	8824737
Fern patch	38	588961	8833045
Fern patch	39	589576	8830196

Category	Id	x	y
Fern patch	40	592336	8832056
Fern patch	41	590595	8835471
Fern patch	42	590686	8835402
Fern patch	43	588376	8838790
Fern patch	44	589427	8838986
Forest	1	590237	8839991
Forest	2	589666	8839523
Forest	3	589963	8838879
Forest	4	590880	8839419
Forest	5	591867	8839510
Forest	6	593294	8838097
Forest	7	594194	8837918
Forest	8	592742	8837128
Forest	9	586351	8838341
Forest	10	585660	8837353
Forest	11	584461	8840276
Forest	12	585271	8840351
Forest	13	580937	8840876
Forest	14	581551	8840771
Forest	15	580949	8837096
Forest	16	578384	8836587
Forest	17	579989	8835223
Forest	18	578626	8833523
Forest	19	581313	8828051
Forest	20	582287	8826925
Forest	21	582263	8826221
Forest	22	582812	8826449
Forest	23	585602	8822154
Forest	24	586950	8821348
Forest	25	587758	8821735
Forest	26	588569	8822707
Forest	27	587641	8823087
Forest	28	593206	8831486
Forest	29	599597	8831980
Forest	30	599957	8831751
Forest	31	578114	8836344
Forest	32	579135	8830177
Forest	33	579151	8830047
Forest	34	580846	8840770

Category	**Id**	**x**	**y**
Forest	35	585524	8837186
Forest	36	586411	8838385
Forest	37	589949	8838834
Forest	38	593116	8838145
Forest	39	594075	8838072
Forest	40	585418	8822275
Forest	41	589873	8831545
Forest	42	590024	8831530
Forest	43	600735	8830224
Forest	44	600390	8830541
Forest	45	601606	8829536
Forest	46	607336	8829551
Forest	47	609674	8830946
Forest	48	588134	8832234
Forest	49	588164	8832309
Forest	50	588254	8832383
Mixed grass	1	588267	8826580
Mixed grass	2	588501	8827623
Mixed grass	3	588306	8825674
Mixed grass	4	588462	8825231
Mixed grass	5	586835	8823180
Mixed grass	6	586614	8822629
Mixed grass	7	586628	8821974
Mixed grass	8	585150	8820686
Mixed grass	9	579082	8822830
Mixed grass	10	578444	8822465
Mixed grass	11	578244	8823127
Mixed grass	12	580193	8821438
Mixed grass	13	579493	8833433
Mixed grass	14	577992	8832960
Mixed grass	15	577320	8833550
Mixed grass	16	580381	8831667
Mixed grass	17	580226	8832991
Mixed grass	18	585878	8827393
Mixed grass	19	586901	8829829
Mixed grass	20	584774	8831311
Mixed grass	21	586099	8833552
Mixed grass	22	596225	8821603
Mixed grass	23	596566	8822360

Category	**Id**	**x**	**y**
Mixed grass	24	597777	8821628
Mixed grass	25	598800	8822710
Mixed grass	26	600146	8824330
Mixed grass	27	600153	8824908
Mixed grass	28	599437	8824684
Mixed grass	29	598755	8825613
Mixed grass	30	600634	8826305
Mixed grass	31	601152	8825996
Mixed grass	32	598752	8828755
Mixed grass	33	599248	8827840
Mixed grass	34	597963	8831572
Mixed grass	35	597707	8831231
Mixed grass	36	596178	8831408
Mixed grass	37	594600	8832355
Mixed grass	38	596158	8835657
Mixed grass	39	595602	8835058
Mixed grass	40	595591	8835519
Mixed grass	41	600829	8837877
Mixed grass	42	602996	8838596
Mixed grass	43	602175	8838790
Mixed grass	44	604244	8836628
Mixed grass	45	589801	8825815
Mixed grass	46	589681	8826251
Mixed grass	47	590327	8826175
Mixed grass	48	593942	8829969
Mixed grass	49	593670	8829835
Mixed grass	50	596925	8829550
Mixed grass	51	595516	8830420
Mixed grass	52	594059	8831635
Mixed grass	53	592481	8832581
Mixed grass	54	590477	8835052
Mixed grass	55	590086	8835881
Mixed grass	56	592140	8836165
Mixed grass	57	585344	8835985
Mixed grass	58	584383	8834756
Mixed grass	59	589754	8838010
Mixed grass	60	588661	8834817
Mixed grass	61	582331	8834498
Mixed grass	62	584024	8833347

Category	Id	x	y
Mixed grass	63	581462	8827375
Mixed grass	64	582529	8828637
Mixed grass	65	581205	8824270
Mixed grass	66	583441	8823295
Mixed grass	67	596567	8817802
Mixed grass	68	597928	8816576
Mixed grass	69	602114	8817743
Mixed grass	70	602283	8819217
Mixed grass	71	601904	8820340
Mixed grass	72	600465	8819906
Mixed grass	73	598995	8819333
Mixed grass	74	601977	8821359
Mixed grass	75	603150	8821627
Mixed grass	76	601816	8824211
Mixed grass	77	596219	8827344
Mixed grass	78	591615	8822051
Mixed grass	79	592591	8820055
Mixed grass	80	590851	8824450
Mixed grass	81	589126	8823011
Mixed grass	82	584851	8838968
Mixed grass	83	584670	8839810
Mixed grass	84	585102	8841624
Pine	1	588683	8831091
Pine	2	589141	8830946
Pine	3	589211	8830456
Pine	4	588866	8830133
Pine	5	588974	8829864
Pine	6	589281	8829180
Pine	7	589582	8829309
Pine	8	589464	8829740
Pine	9	589168	8830090
Pine	10	588699	8830607
Pine	11	588963	8830730
Pine	12	590121	8831145
Pine	13	590018	8830989
Pine	14	589787	8830989
Pine	15	589232	8831140
Pine	16	587041	8830763
Pine	17	587036	8830531

Category	Id	x	y
Pine	18	586820	8830332
Pine	19	589394	8830730
Pine	20	589184	8829417
Pine	21	589119	8832496
Pine	22	588855	8832545
Pine	23	588608	8832685
Pine	24	587456	8832534
Pine	25	587273	8832486
Pine	26	587267	8831979
Pine	27	587090	8831737
Pine	28	588032	8831823
Pure grass	1	593146	8827481
Pure grass	2	593263	8826468
Pure grass	3	593487	8825415
Pure grass	4	594978	8825747
Pure grass	5	595982	8826234
Pure grass	6	594735	8827959
Pure grass	7	593151	8828801
Pure grass	8	592201	8827978
Pure grass	9	592135	8829547
Pure grass	10	585600	8826992
Pure grass	11	586450	8825445
Pure grass	12	587463	8826424
Pure grass	13	595614	8828787
Pure grass	14	597134	8827569
Pure grass	15	589289	8827979
Pure grass	16	591388	8828529
Pure grass	17	591710	8827686
Pure grass	18	593709	8828334
Pure grass	19	590676	8832256
Pure grass	20	591183	8832783
Pure grass	21	595470	8832895
Pure grass	22	595071	8833927
Pure grass	23	594135	8833825
Pure grass	24	596483	8832315
Pure grass	25	593392	8834658
Pure grass	26	592769	8834532
Pure grass	27	596030	8837245
Pure grass	28	595753	8837470

Category	Id	x	y
Pure grass	29	596700	8837762
Pure grass	30	599177	8838122
Pure grass	31	594569	8843113
Pure grass	32	595606	8843847
Pure grass	33	596488	8843574
Pure grass	34	596985	8842642
Pure grass	35	587153	8835271
Pure grass	36	587202	8835549
Pure grass	37	583714	8835705
Pure grass	38	584518	8835748
Pure grass	39	583889	8835325
Pure grass	40	584071	8835053
Pure grass	41	582784	8837053
Pure grass	42	582974	8837382
Pure grass	43	581348	8837216
Pure grass	44	580233	8837757
Pure grass	45	580939	8837818
Pure grass	46	579458	8830432
Pure grass	47	579906	8830398
Pure grass	48	581373	8830222
Pure grass	49	578747	8830763
Pure grass	50	587463	8822057
Pure grass	51	586927	8821686
Pure grass	52	585957	8823133
Pure grass	53	589054	8820622
Pure grass	54	586350	8822069
Pure grass	55	578985	8823536
Pure grass	56	579605	8831884
Pure grass	57	578538	8831937
Pure grass	58	579763	8834268
Pure grass	59	596912	8821739
Pure grass	60	598614	8829153
Pure grass	61	596459	8831844
Scar_Mild	1	588810	8836258
Scar_Mild	2	591211	8835770
Scar_Mild	3	599663	8839160
Scar_Mild	4	592409	8836386
Scar_Mild	5	588928	8838027
Scar_Mild	6	591048	8838042

Category	Id	x	y
Scar_Mild	7	592808	8838224
Scar_Mild	8	591469	8838880
Scar_Mild	9	590411	8839691
Scar_Mild	10	589949	8838250
Scar_Mild	11	590002	8839998
Scar_Mild	12	590066	8836149
Scar_Mild	13	589993	8833479
Scar_Mild	14	590832	8834428
Scar_Mild	15	590625	8835356
Scar_Mild	16	588522	8834562
Scar_Mild	17	591507	8834154
Scar_Mild	18	594089	8831485
Scar_Mild	19	594916	8831201
Scar_Mild	20	595095	8830449
Scar_Mild	21	595006	8829655
Scar_Mild	22	594074	8829928
Scar_Mild	23	596940	8829309
Scar_Mild	24	596743	8828248
Scar_Mild	25	595948	8828232
Scar_Mild	26	598020	8827692
Scar_Mild	27	591689	8824805
Scar_Mild	28	592634	8824555
Scar_Mild	29	594121	8820280
Scar_Mild	30	603858	8817443
Scar_Mild	31	601216	8821555
Scar_Mild	32	590699	8825815
Scar_Mild	33	587939	8824749
Scar_Mild	34	588525	8823058
Scar_Mild	35	580050	8826146
Scar_Mild	36	581657	8825830
Scar_Mild	37	581610	8826788
Scar_Mild	38	590448	8815030
Scar_Mild	39	582615	8828860
Scar_Mild	40	582734	8832475
Scar_Mild	41	582300	8834260
Scar_Mild	42	584462	8832895
Scar_Mild	43	584635	8837827
Scar_Mild	44	586170	8836581
Scar_Mild	45	588089	8837741

Category	Id	x	y
Scar_Mild	46	587309	8838551
Scar_Severe	1	585289	8828577
Scar_Severe	2	585759	8829125
Scar_Severe	3	584863	8829513
Scar_Severe	4	586256	8829676
Scar_Severe	5	583844	8829186
Scar_Severe	6	584867	8830168
Scar_Severe	7	583496	8829873
Scar_Severe	8	583980	8828089
Scar_Severe	9	584259	8827119