THE VALUE OF USING LANDSAT 8 INDICES TO DESCRIBE LARGE HERBIVORE DISTRIBUTION

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DECLARATION

I declare that this dissertation is my own, unaided, original work. It is being submitted for the Master of Science degree at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or any other examination at any other university.

(Signature of candidate)

19 May 2016

ABSTRACT

Satellite imagery and remote sensing techniques provide a way to collect data over large temporal and spatial scales, and build indices that gauge ecological variables. These indices can explain the distribution of animals in their environment. In this study I compare the ability of various indices derived from Landsat 8, to reliably predict locations of different large herbivore species across diverse habitats. The study was undertaken in the Kgaswane Mountain Reserve, North West Province, South Africa. Daily locations of two herds of sable antelope (*Hippotragus niger*) and one herd of eland (*Tragelaphus oryx*) were used. One sable antelope herd (vlei herd) occupied a grassland plateau with a wetland and the other sable antelope herd (woodland herd), shared the wooded area at the base of the mountains with the eland herd. I described vegetation communities, burnt areas, geology and soil templates at animal locations during foraging bouts in the dry season; coinciding with the times of the Landsat images.

The overall aim of this study was to see whether an index or a combination of indices could better describe animal locations than the normally used NDVI. I calculated a number of indices, and compared their predictive ability to define areas used by the study animals. Specifically, I compared the Normalised Difference Vegetation Index (NDVI) to Soil Adjusted Vegetation Index (SAVI), Visible Atmospherically Resistant Index (VARIgreen), Green Atmospherically Resistant Index (GARI), Normalised Difference Water Index (NDWI), a proxy for soil moisture; and mineral composite indices assessing clay minerals, ferrous minerals and iron oxide. I chose these indices as they describe the basic characteristics of an ecologically functioning unit.

The locations of one of the sable antelope herds, located in grassland areas underlined by quartzite, were best described by NDVI, SAVI and VARIgreen. The locations of the other sable antelope herd, occurring in an open wooded area with shallow sandy soils on norite and quartzite, were best described by clay minerals and GARI. Eland locations, found in woodland areas characterised by deep norite soils, were best described by a combination of iron oxide, NDVI and SAVI.

Therefore, NDVI proved to be an adequate indicator in open grassland areas, where it could be interchanged with SAVI, and improved by VARIgreen. In closed woodlands NDVI, SAVI and NDWI could all be used to describe browser locations. NDVI was not a suitable index when it came to describe locations of a grazer in a woodland/grassland matrix. However, it is important to keep in mind that my results pertain only to one dry season and two herbivore species, and therefore further studies would be needed to be able to generalise the results further.

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LIST OF ABBREVIATIONS AND ACRONYMS

△AIC - delta AIC

˚C - degrees centigrade

Abl. - Ablution block

Admin. - Administration building

AIC - Akaike information procedure

AICc - version of the Akaike information procedure, corrected for small samples

ARVI - Atmospherically Resistant Vegetation Index

AWT - Africa Wildlife Tracking

Df - degrees of freedom

ESA - European Space Agency

et al.- *et alia* and others

ETM+ - Enhanced Thematic Mapper

GARI - Green Atmospherically Resistant Index

GIS - Geographic Information Systems

Glm - generalised linear model

GPS - Global Positioning System

Gs - Glenrosa Soil Form

Hu - Hutton Soil Form

KMR - Kgaswane Mountain Reserve

L - a graphical line (soil line) indicating the soil spectral variation vs. increasing soil brightness

MCP - Multiple Convex Polygon

MODIS - Moderate Resolution Image Spectrometer

Ms - Mispah Soil Form

ND - No Date

NDVI - Normalised Difference Vegetation Index

NDWI - Normalised Difference Water Index

NIR - near infrared

Ob - other burns

OLI - Operational Land Imager

PAN - panchromatic band

Pb - Prescribed burn

pers. comm. - personal communication

R - R Development Core Team

SAVI - Soil Adjusted Vegetation Index

Sb - security burn

SWIR - short wave infrared

TIR - thermal infrared

TIRS - Thermal Infrared Sensor

TM - Landsat Thematic Mapper

USGS - United States Geological Survey

UTM - Universal Transverse Mercator

VARIgreen - Visible Atmospherically Resistant Index

WGS - World Geodetic System

Wi (AICc) - rounded AIC weights

CHAPTER 1

GENERAL INTRODUCTION

Broad project aim

The aim of this project is to test the value of a range of spectral indices derived from Landsat 8 to describe the locations of large herbivores within the landscape; in order to establish whether there is a better indicator of animal resource use than greenness as determined by Normalised Difference Vegetation Index (NDVI).

Motivation of study

African ungulates across southern African game reserves are declining (Owen-Smith *et al.* 2012). This is partly attributed to fragmentation of previously larger seasonal home ranges (Newmark 2008; Primack 2010), shifting plant phenology due to climate change (Newmark 2008; Primack 2010) and bush encroachment or desertification caused by changing land use (Wagenseil and Samimi 2006). In South Africa animal movement is further limited by boundaries imposed by fenced game reserves (Coughenour 1991; Owen-Smith *et al*. 2012). These pressures contribute towards the modification of historically functioning ecological units, by altering forage and water availability and cutting off natural movements towards optimal resources (McCarty 2001; Boone and Hobbs, 2004; Milly *et al*. 2008). Therefore, the understanding of animal locations within the landscape in relation to forage resources may provide insight into the decline of African ungulates.

The Normalised Difference Vegetation Index (NDVI), which is related to the chlorophyll content of vegetation, has been commonly used to determine the relationship between animal locations and available resources (Pettorelli *et al.* 2005 a; Zeng *et al.* 2010; Marshal *et al.* 2011; Pettorelli *et al.* 2011; Bischof *et al.* 2012). Many studies have linked animal movement patterns to NDVI, using NDVI derived from the MODIS platform (Pettorelli *et al.* 2005 a; Zeng *et al.* 2010; Pettorelli *et al.* 2011; Bischof *et al.* 2012) with a spatial resolution of 250-500 m (Allen *et al.* 2008). However, studies looking at resource selection across various spatial scales, have pointed out how the spatial resolution of MODIS might not be adequate to represent the actual scale at which large herbivores select for resources (Marceau and Hay, 1999; Huete *et al*. 2002; Reeves *et al*. 2005) and resource selection may occur at smaller scales than that defined by MODIS (Parrini 2006; Archibald and Scholes 2007; Boyers 2011; Mokoena 2012). This study focuses on indices derived from Landsat 8 imagery; with a spatial resolution of 30 m for visible, near infrared (NIR) and short wave infrared (SWIR) bands and 15 m for the panchromatic band (Loyd 2013). Heitkonig *et al.* (2003) linked the distribution of large herbivores in the Okovango Delta in Botswana to Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) data; Van Bommel *et al.* (2006) used NDVI derived from Landsat 7 ETM+ images in conjunction with GPS collared impala (*Aepyceros melampus*) to determine habitat preferences also in the Okovango Delta in Botswana; and Bechtel *et al*. (2004) related Landsat 5 TM imagery to the use and avoidance of areas by woodland caribou (*Rangifer tarandus caribou*) in Canada.

Therefore the aim of this study is to test if additional indices, besides NDVI, could be used to explain animal locations within the landscape. At a basic level of ecological functioning, it seemed appropriate to test indicators of vegetation greenness, soil moisture and mineral composites as these are fundamental characteristics required to sustain high quality forage, which influences animal distribution (McNaughton 1988; McNaughton, 1990; Ydenberg *et al.* 1992; Frank *et al.* 1998). The vegetation indices included, apart from NDVI, are SAVI to compensate for soil reflectivity in a heterogeneous environment (Najeeb 2013) and the atmospherically resistant greenness indices VARIgreen and GARI. These are included in this study to test whether a response to green biomass could be made more evident using indices correcting for atmospheric pollution, as the study area was close to an urban and industrialised area. Soil moisture indices and indices of moisture within vegetation are transposable (Loyd, *pers. comm.* 2014) and both will effect animal distribution, as herbivores prefer vegetation with higher water content (Besnard *et al.* 2013). Because indices of moisture within the vegetation are more straightforward to calculate, NDWI was chosen (Loyd, *pers comm,* 2014). Mineral composite indices including clay minerals, iron oxide, and ferrous minerals can be calculated from multispectral satellite data (Dogan,

2009) and are adequate for the purposes of this study. As the study area is small, ground water availability is not a limiting factor, so this was not tested.

Literature review

Factors affecting animals' locations in space and time

Herbivores make decisions where to forage on many different levels from the entire landscape, to within their home range, to which tuft of grass is preferable to eat (Senft *et al.* 1987). Landsat's spatial resolution of 15 to 30 m (Loyd 2013) means it is not able to differentiate between varied vegetation types or plant species and is only capable of gathering information about landscape or regional scales (Forshaw *et al*. 1983; Kerr & Ostrovsky 2003). Consequently the information collected from Landsat indices must be used in conjunction with biological knowledge about the environment and the animal species in question; acquired from literature, ecological modelling, or ground truthing (Levin 1992; Leyequien *et al*. 2007).

The study of animal locations within a landscape, which is the focus of this study, contributes towards an understanding of various aspects of ecology including foraging choices, space use inside the home range and movement patterns (Bell 1971; Senft *et al*. 1987). Broadly speaking, the main factors influencing the location of herbivores within the landscape can be divided into biotic and abiotic components. Abiotic factors comprise water availability, which is effected by seasonal rainfall (Frank *et al.* 1998); distance to water (Bailey 2005), shelter from unsuitable weather conditions (Afolayan and Ajayi 2008) and topography (Bailey 2005; Coughenour 1991). Abiotic factors also include the accessibility of nutrients, which are linked to fire (McNaughton 1985; Frank *et al.* 1998; Fuhlendorf and Engel 2004), underlying soil type and the geological template (Rodriguez-Iturbe 2000). Biotic factors refer to competition, disease (Pienaar 1974), predation and resource availability (Bailey *et al*. 1996; Bailey 2005). Mostly, large herbivores are utilising vegetation that varies spatially and seasonally with regards to quality and quantity (McNaughton 1988; McNaughton, 1990; Frank *et al.* 1998) and they need to find high quality food sources, while using the least amount of physiological energy (Ydenberg *et al.* 1992). The consumption of vegetation by herbivores both creates and uses primary productivity; thus influencing the amount of forage, the rate of production and the quality of food that is available (McNaughton 1985; McNaughton *et al*. 1988; Bailey *et al.* 1996). Plants have characteristics that can be measured and relate to quantity, such as biomass and grass height (Sinclair 1985; Ben-Shahar 1995); and other characteristics relating to quality, such as mineral concentrations, digestibility and greenness (McNaughton 1985; Sinclair 1985). Biotic factors are mostly limited by abiotic factors (Oom *et al*. 2004). Therefore, when studying ecosystems at landscape scale; both biotic and abiotic factors converge to explain animal distribution (Redfern *et al.* 2003) and below I review the factors that are relevant to this study.

Quality, quantity, and spatial and temporal distribution of vegetation

Rainfall is a principal driver of ecological processes in savannas and grasslands (Hoffmann and Jackson 2000; Hawkins *et al.* 2003). In the wet season, grasses become photosynthetic almost simultaneously, creating a ‘green wave’ across the landscape (Frank *et al.* 1998). This phenomenon is driven by rainfall and soil moisture (Porporato *et al.* 2004). As grasses are grazed; their leaves regenerate, causing a homogeneous vegetation type throughout the grassland (Jarman 1974; Coughenour 1985; Frank *et al.* 1998). The increased level of nutrients in the leaves of new grass is because of a larger leaf - stem ratio over a smaller amount of above-ground biomass than that found in established vegetation (Van der Vijver *et al*. 1999). Plant maturity is also synchronised in grasses, so the growing season from the emergence of protein-rich new leaves to the lignification of carbohydrate-rich older leaves happens concurrently over a short space of time (Jarman 1974).

Trees have deeper roots than grasses so they can access sub-surface soil moisture and are not so reliant on the rains at the onset of the wet season, which creates a more heterogeneous environment where woodland is present (Borchert 1999). Trees may in fact initiate their first spring buds due to photoperiod (change in light), relying on stored water and carbohydrates within the plant (Archibald and Scholes 2007). This means that their growing period is longer than grasses and they can contain emerging buds, growing leaves and mature leaves all on the same plant (Jarman 1974). Trees have an apical meristem, so only the tip of the bud contains growth tissue and therefore a smaller part of the plant will be growing at any time compared to grasses (Weier *et al*. 1974). Moreover, trees may have differing green-up times depending on tree size (Novellie 1989); soil type, slope aspect and catena position (Shackleton 1999). Each vegetation community will therefore contain differing amounts of green foliage depending on the composition of deciduous, semi- deciduous and evergreen trees (Borchert 1999).

As grass and tree leaves mature, they increase in biomass but lose nutritional quality (Owen-Smith 1982; Owen-Smith and Novellie 1982) and mature tree leaves can concentrate secondary metabolites that are unpalatable or even toxic to browsers (Cooper *et al*. 1988). For both trees and grasses, forage value drops once photosynthesis stops and dormancy occurs (Weier *et al*. 1974). This is the time when animals are most vulnerable to resource limitations and must choose between finding high quality forage or compromise by eating larger quantities of low quality food (Bailey *et al*. 1998). In the dry season, some grass species still remain green, particularly if they grow in areas that retain soil nutrients and moisture (Anderson and Kneale 1980; McNaughton 1985; Scoones 1991). This forces animals to travel further during the dry season than they do in the wet season to seek greener forage; or to stay in areas that have become sub-optimal with regard to resources and tolerate less palatable grass species (Parrini 2006).

Water availability

As rainfall is seasonal, herbivores are mostly affected by water constraints in the dry season, and this will influence their distribution relative to water and food depending on the physiological needs of each species (Redfern *et al.* 2003; Smit and Grant 2009). Herbivores are to a greater or lesser degree dependent on water that they obtain from moisture content in forage (Besnard *et al.* 2013). Grazers are generally more dependent on water than browsers during the dry season (Western 1975) because the moisture content in grass is mostly below 10%, while leaves of trees and shrubs have a moisture content of about 30% (Kay 1997). Therefore the distance animals can move from water in order to obtain the necessary forage quality and quantity depends on their species-specific water requirements and their ability to obtain water from food, particularly during the dry season when plant water content decreases due to senescence (Nippert *et al.* 2013). At this time surface water is limited and many water-dependent herbivore species concentrate in areas close to water (Western 1975). Some species, such as sable antelope (*Hippotragus niger*), have been found to travel further from water during the dry season than in the wet season in order to forage without the stress of competition from other ungulates or the predation risks that concentrated grazing closer to water brings (Smit and Grant 2009). For example, in the Kruger National Park, Cain *et al.* (2012) found that sable antelope only needed to drink at two to four day intervals in the dry season compared to zebra (*Equus quagga*) that drank every one to two days. Therefore sable could cover more ground than zebra, seeking greener patches of forage. As mixed feeders, eland (*Tragelaphus oryx*) tend to browse in the dry season and are more water-independent than sable (Western 1975). Eland drink opportunistically and can rely on the moisture within leaves to supply their water requirements (Smithers 1986; Rudee 2011). For example (Field 1975), studying eland at the Galana Ranch in Kenya, found that during the dry season they did not remain in dry grassland, but moved to areas with higher browse found on evergreen trees.

Soil moisture

The distribution of soil moisture across a landscape is a complex interaction between the physical properties of weather conditions, season, topography, soil type, nutrient availability, vegetation type, fire, grazing pressure, and even the time of the day (Porporato and Rodriguez-Iturbe 2002). The consequences of these dynamics make the prediction of soil moisture difficult (Houser *et al.* 1998; Moran *et al.* 2004). Soil moisture acts as a reservoir for the water cycle and influences run off, evapotranspiration and drainage of excess rainwater when ground water is saturated (Western *et al.* 2002). It is the water that is available to plants in their root zone, affecting plant growth processes (Lobell and Asner 2002) and by proxy, plant and animal distribution patterns (Western *et al.* 2002; Wang and Qu 2009). This availability varies seasonally, which leads to both spatial and temporal fluctuations of water across the landscape (Grayson *et al.* 1997).

Soil moisture is a core factor involving vegetation distribution (Porporato and Rodriguez-Iturbe 2002) as the relationship between soil moisture and transpiration is both the source and the outcome of heterogeniety in vegetation growth (Tromp-van Meerveld and McDonnell 2006). This is because different plant species will have different rates of root water uptake and transpiration (Ludwig *et al*. 2004). In their work in the Kalahari Desert, D'Odorico *et al.* (2007) found that the relationship between soil moisture and vegetation is an important factor determining the structure and function of arid and semi-arid ecosystems, because the presence of soil moisture in patches across a landscape will dictate areas of plant growth. Soil moisture availability during the wet season initiates grass production, but it is soil nutrients that control the growth rate during this period, which leads to pulses of rapid growth followed by dormancy (McNaughton *et al*. 1988; Scholes 1990).

Soil mineral content

Soil mineral content in vegetation is an important factor in forage choice and spatial and temporal distribution of herbivores, as they obtain minerals indirectly from plants (McNaughton 1988). Therefore, there is a connection between soil minerals, plant distribution and animal movement (Lillesand *et al.* 2008). It is expected that animals will select grazing areas with required concentrations of essential trace minerals (McNaughton 1988) and in fact McNaughton (1990) found that the migration of herbivores in the Serengeti National Park was not only associated with soil moisture and vegetation quality, but also with the seasonal availability of minerals in the soil.

Minerals within the soil and soil fertility are determined by the type of weatherable minerals in the sand and silt fractions, and the number of ion exchange sites in the clay fraction (Palm *et al.* 2007). Primary minerals are formed by geological processes creating the parent material of soils and providing a reservoir of all nutrients, except for nitrogen; and secondary minerals are produced by weathering processes in the clay fraction (Palm *et al.* 2007). Clay minerals are responsible for soil structure and porosity (Palm *et al*, 2007), which influences soil moisture and the movement and retention of nutrients in the soil (Dogan 2009). Nitrogen is a primary mineral that is of critical value to plants as it is a component of protein; producing plant tissue, chlorophyll, enzymes and nucleic acids needed for vegetative and reproductive parts of the life cycle (Ohyama 2010). It becomes available intermittently because of inputs of organic matter in the soil and the subsequent activity of nitrogen-fixing soil microbes (Nord and Lynch 2009). For example, Acacia trees are nitrogen-fixing leguminous plants that can stimulate the nutrient content in plants growing beneath them (Danso *et al.* 1992; Power *et al.* 2003), although Belsky (1994) found that there was also increased nitrogen available to grasses growing beneath non-leguminous *Adansonia digitata* (Baobab) trees. Also, litter fall beneath trees causes deposition and decomposition of organic matter; improving the soil's capacity to retain nutrients and increasing nutrient availability (Sutton *et al.* 2002). Tree roots act as nutrient pumps; causing inaccessible nutrients that are deep below the soil surface to become available to grasses growing close to or beneath tree canopies (Scholes 1990). Therefore grass quality is enriched under canopies; and during the dry season grasses such as *Panicum maximum* that grow beneath leguminous trees become an important source of nutrition for herbivores (Van Der Merwe and Marshal 2012).

Fire

Nutrient pulses within savanna and grassland biomes are also caused by fire (McNaughton 1985). The interaction between fire and grazing is dynamic in space and time and it affects vegetation heterogeneity at different scales by creating a fluctuating patchwork of plant growth throughout the landscape (Fuhlendorf *et al.* 2008). Burnt patches are so appealing to some species of herbivores that they will move towards green flushes, even if this takes them outside their usual home ranges (Parrini and Owen-Smith 2010). Forage quality of plants in recently burned areas can be two to three times greater than in areas that have not been burned for a longer period of time (Allred *et al.* 2011). Therefore, upon finding a burnt patch; herbivores may change their foraging strategy and either quickly pass through the patch; or remain for an extended time, depending on the patch size and the availability of high quality forage (Kerby 2000). For example, a burn during the dry season may contain enough high quality food for sable antelope to increase their foraging time in the patch, even though the quantity of forage is lower than in surrounding unburned areas (Parrini and Owen-Smith 2010).

Consideration must be given to the fact that the use of burnt areas is dependent on the species of ungulate, their feeding preferences and the time of the year (Gureja and Owen-Smith 2002). In their observations at the Madrid Game Ranch, near Klaserie in South Africa; Gureja and Owen-Smith (2002) found that roan antelope (*Hippotragus equinus*), Lichtenstein's hartebeest (*Alcelaphus lichtensteini*), tsessebe *(Damaliscus lunatus*), sable antelope and zebra all foraged in burnt areas, but each species selected different types of localities according to their forage and behavioural requirements. The roan preferred burns in woody areas, where they ate tall grass species. They grazed mainly in bottomlands together with the hartebeest; whereas tsessebe, zebra and sable antelope used the mid-slope or upland burns.

Foraging behaviour

A basic knowledge of foraging behaviour, although not being the focus of this study, is essential to interpret large scale, landscape level distribution patterns. Body size and digestive physiology determine the range of food that herbivores can tolerate, and therefore determine how they disperse in the landscape (Owen-Smith 1982). The food available to herbivores is mainly abundant, low quality forage, mixed with variable patches of higher quality vegetation (Jarman 1974; Senft *et al.* 1987). The area over which an animal moves to find its food depends on its unique physiology and metabolic requirements and the presence of sufficient forage to fulfill these requirements (Owen-Smith 1982). The way in which a species of herbivore digests food makes it more or less reliant on forage quality or quantity (Pyke *et al*. 1977; Hanley 1982; Senft *et al.* 1987; Ydenberg *et al.* 1992). This is influenced by the physiological limitations of the animal; for example body and muzzle size and digestive system (Owen-Smith 1982). Feeding preferences for African herbivores range from pure grazers, to mixed feeders preferring graze, to mixed feeders preferring browse, to pure browsers (McNaughton and Georgiadis 1986). Within this range herbivores can be further categorised by whether they are generalist or selective feeders (Jarman 1974); and whether they are ruminants or non-ruminants (Bell 1971).

Large bodied herbivores have a slower metabolic rate per unit of body tissue than small bodied herbivores so they need to eat more (Owen-Smith 1982). They tend to be generalist feeders, tolerant of a wide range of forage (McNaughton and Georgiadis 1986) and can make use of a greater quantity of fibrous food with low nutritive quality to fulfill their nutritional needs (Geist 1974; Jarman 1974; Owen-Smith 1982; Demment and Van Soest 1985; Illius and Gordon 1992). For example zebra, a non-ruminant generalist feeder, can tolerate more indigestible vegetation than ruminant grazers of equivalent size because they are hindgut fermenters (Bell 1971). However, ruminating grazers such as sable antelope are limited by a longer gut retention time and so they require high quality forage (Illius and Gordon 1992). Owen-Smith *et al.* (2013) found that in the Kruger National Park, sable antelope, which are medium-sized grazing ruminants, were only selecting the green leaves left on grass in the dry season, even though they tolerated the same grass species as zebra. Eland are large mixed feeding ruminants (Lamprey 1963) and are the most adaptive of generalists; able to switch between grazing and browsing depending on the food supplies available (Van Soest 1996). The kudu (*Tragelaphus strepsiceros*), is a browsing ruminant with a wide dietary range in order to support its large body size (Owen-Smith and Novellie 1982). Small bodied herbivores have higher energy demands and can extract energy from food at a higher rate than large bodied herbivores (Demment and Van Soest 1985; McNaughton and Georgiadis 1986), so they mostly select plants or parts of plants with high nutritional quality (Fryxell 1991). They are often selective feeders that tolerate specialised and localised plant species (Perez-Barberia and Gordon 2001). For example klipspringer (*Oreotragus oreotragus*) and bushbuck (*Tragelaphus scriptus*) are small ruminant browsers restricted to specific habitats (Pienaar 1974). Generalist grazers tend to have wider muzzles than selective grazers because they need to maximise the intake of low quality forage by consuming large bites of grass, whereas selective grazers need a narrow muzzle to choose certain plant parts in a stand of vegetation (Owen-Smith 1982; Illius and Gordon 1987). Browsers usually have a narrower dental arcade and a wider mouth opening than grazers, which enable them to efficiently select and strip specific plant parts (Janis and Ehrhardt 1988).

Satellite Indices

The study of many ecological processes requires data at large spatial scales, often incorporating inaccessible areas where it is costly and impractical to physically collect data (Kerr and Ostrovsky 2003). Satellite imagery and remote sensing techniques enable researchers to collect data over large areas and integrate it with ecological models and field work to interpret environmental processes (Levin 1992). Satellite sensors capture light that hits a target area on the Earth’s surface. This light is reflected, transmitted, or absorbed, depending on the characteristics of the surface and the wavelength of the light (Jackson and Huete 1991). This information is used to create indices that measure variables, which can explain various ecological characteristics at a landscape level (Escadafal and Huete 1992).

Most of the indices I will be using in this study, have to date not been used in relation to animal movements. Although some indices have been used in animal movement studies, I could not find much literature relating animal distribution to the other indices used in this study. Therefore, below I review what the various indices measure, their advantages and limitations, and I will review relevant literature if they have previously been used in animal movement studies, and if not used in this kind of studies before, I will provide supporting information on why I think they could be useful in animal movement studies.

Vegetation Indices

Vegetation Indices are empirical equations that relate to certain characteristics of vegetation (Philpot 2011). They are constructed on the premise that primary productivity, biomass and nutritional quality can be inferred from multispectral reflectance of vegetation cover due to the processes of photosynthesis and evapotranspiration (Basso *et al*. 2004). In order to be useful, vegetation indices must be able to register subtle changes in plant health compared with a standard, known reflectance of healthy plant biomass, whilst taking into account a number of variables such as atmospheric interference, sensor view and solar zenith angles, soil background and canopy reflectance (Jackson and Huete 1991).

Green plants, along with other features on the Earth’s surface, reflect infrared wavelengths (Philpot 2011; Gillieson *et al.* 2006); while photosynthetically active plants reflect green and near infrared (NIR) wavelengths and absorb red wavelengths (Myneni *et al.* 2005). The spectral signature of plants is characterised by low reflectance in the visible part of the spectrum and high reflectance in the NIR part of the spectrum (Pinty and Verstraete 1992). This characteristic of vegetation can be remotely measured by means of the generally used Normalised Difference Vegetation Index (NDVI) (Lillesand *et al.* 2008).

The NDVI equation is derived from the red: NIR reflectance ratio (Rouse *et al.* 1973). It is based on the fact that chlorophyll, indicating greenness in leaves, absorbs red light for use in photosynthesis; and the cell structure of mesophyll reflects NIR light (Myneni *et al.* 2005). The visible and thermal sensors on the satellite platform captures both the red and infrared bands of the spectrum (ESA, 2013) and comparison of the reflectance ratio between these two bands for each pixel in the image gives an idea of vegetation condition, because the higher the ratio between the bands, the more photosynthetically active the vegetation is (Gitelson *et al.* 1996). The range of NDVI values are between -1 and +1 (Mather 2007; Myneni *et al.* 2005); where high NDVI values are usually linked to a continuous green layer such as unbroken grassland or closed canopy woodland, and low NDVI values are associated with non-continuous vegetation cover, such as areas with exposed soil (Van Bommel *et al.* 2006) or an absence of vegetation or senesced leaves (Pettorelli *et al.* 2005 a). Bare soil and cloud have NDVI values close to zero and water has a negative NDVI value (Mather 2007; Lillesand *et al.* 2007; Neigh *et al.* 2008). NDVI is a useful tool as it can show how spatial and temporal distribution of plant cover, plant phenology, primary productivity and photosynthetic activity is linked to animal movements (Beck *et al.* 2008; Pettorelli *et al.* 2011). It relates to plant qualities that are important to herbivores such as crude protein concentration, nitrogen concentration and fibre content (Albayrak 2008); which means that it can measure forage characteristics that influence herbivore fitness (Winnie *et al.* 2008). NDVI seems to be associated with animal locations in many studies (Pettorelli *et al*. 2005 b; Marshal *et al.* 2011; Bischof *et al.* 2012); but not all studies (Verlinden and Masogo 1997).

However, as with all vegetation indices, NDVI has its limitations. Remote sensing of vegetation involves the unintended measurement of other components alongside vegetation, such as soil or atmosphere; and vegetation indices are only useful if these non-vegetation components can be separated from the data explaining the vegetation component (Huete *et al.* 1985). There are many factors that affect NDVI values within one pixel, such as plant architecture and height, species composition, vegetation vigour, topography and altitude (Mather 2007; Pettorelli *et al.* 2005 a; Lillesand *et al.* 2007). Consequently, the same NDVI value might represent different conditions in different plant communities (Jackson and Pinter 1986). Depending on the spatial resolution of each pixel, it is difficult to identify whether the NDVI values represent quality (greenness) or quantity (biomass) of the vegetation, which means that the same NDVI value may represent different conditions in different plant communities at different times (Pettorelli *et al*. 2005 a; Winnie *et al.* 2008).

NDVI also has limited use in areas that are not vegetated for large parts of the year (Pettorelli *et al.* 2011). This is because the interference of exposed soil can alter the red: NIR reflectance ratio (Escadafal and Huete 1992), depending on the soil type; its texture (Huete and Jackson 1988), colour (Huete *et al.* 1985), amount of organic matter and the variation in soil moisture content (Huete and Jackson 1988). Therefore on partially or unvegetated soils, different soil types will record different NDVI values (Escadafal and Huete 1992) in such a way that the darker the soil substrate, the higher the NDVI values (Huete and Jackson 1988). Soil brightness and reflectivity influence partially vegetated soils more than soils that are completely covered by vegetation; so vegetation index values are to a certain extent dependent on soil index values (Huete *et al.* 1985; Huete and Jackson 1988; Najeeb 2013).

Most vegetation indices have been developed over homogenous canopies using croplands to calculate biomass, but in natural environments vegetation is more heterogeneous and vegetation index values may deviate from the expected standard (Huete and Jackson 1987). This is because in natural grasslands and savannas vegetation diversity is influenced by differing amounts of dry matter accumulation and decomposition rates; varying soil types and topography (Huete and Jackson 1987).

Diversity is also affected by short periods of rapid growth caused by rainfall (Scholes 1990) and fire (Fuhlendorf *et al.* 2008); followed by vegetation depletion due to grazing (Huete and Jackson 1987). Therefore other vegetation indices may be more valuable than NDVI when working in arid and semi-arid areas. One example is the Soil Adjusted Vegetation Index (SAVI), which was developed by Huete (1988) as it corrects for soil brightness, especially when vegetation cover is only partial (Najeeb 2013). SAVI gives better estimates of heterogeneous vegetation cover, where soil reflectance varies (Huete *et al.* 1985; Huete and Jackson 1988; Escadafal and Huete 1992; Najeeb 2013).

In general, most vegetation indices are sensitive to atmospheric effects such as high volumes of aerosols, smoke or clouds, which cause turbidity and therefore decrease the accuracy of the index (Holben, 1986; Xiao *et al.* 2003). Atmospheric particles interact with incoming solar radiation in such a way that they cause an increase in red band reflectance (Kaufman and Tanre 1992). In the NIR band there is not such a pronounced influence by the atmosphere because although there is an increase in surface reflectance due to aerosol scattering, this is partially cancelled out by a decrease in reflectance due to aerosol absorption (Gitelson *et al.* 1996). Nevertheless, the interference in the red band can decrease the value of vegetation indices (Holben 1986). Atmospherically resistant indices have been developed to correct for the effect of the atmosphere on the red band; the initial index being the Atmospherically Resistant Vegetation Index (ARVI) developed by Kaufman and Tanre (1992), which uses the visible blue band to decrease the effects of scattering (Gitelson *et al.* 1996). From the basis of this index, other atmospherically resilient vegetation indices have been derived. This has been achieved by using the difference in radiance between the blue and red bands to correct for the influence of atmospheric aerosols on the red band (Kaufman and Tanre 1992).

The Green Atmospherically Resistant Index (GARI) was developed by Gitelson *et al.* (1996). This is superior to ARVI in that it is sensitive to pigment in the vegetation whilst still being resistant to atmospheric effects (Gitelson *et al.* 1996). ARVI and NDVI both use the ratio between red and NIR bands to measure photosynthetic rate by means of the solar photosynthetically active radiation absorbed by plants (Sellers 1985). ARVI includes the blue band in the equation to decrease errors to the index value caused by atmospheric scattering (Kaufman and Tanre 1992). GARI substitutes the green for the red band because the green band can sense the changes in the concentration of chlorophyll within the leaf, which aids monitoring plant stress or senescence (Gitelson *et al.* 1996). At the same time GARI corrects for atmospheric effects by calculating the difference in reflectance between the blue and the red channels (Gitelson *et al.* 1996). Another atmospherically sensitive vegetation index, the Visible Atmospherically Resistant Index (VARIgreen) was developed by Gitelson *et al.* (2002), which include both the green and blue bands to compensate for atmospheric effects. Gitelson *et al.* (2002) plotted the vegetation fraction for wheat (*Triticum aestivum*) versus both NDVI and VARIgreen by comparison, using MODIS spectral channels. NDVI was most sensitive for a vegetation fraction between 0% and 50%, after which it levelled off. VARIgreen remained sensitive to the vegetation fraction from 0% to 100%.

Atmospheric indices have been used in precision farming (Tanriverdi 2006) to identify vegetation health and phenological transitions in crop science (Jackson *et al.* 1983; Gitelson *et al.* 2002; Vina, *et al.* 2004; Jiminez-Munoz 2009), monitor moisture content in vegetation (Stow *et al*. 2005), monitor photosynthesis rate and plant stress (Gitelson *et al.* 1996), map fire risk (Peterson *et al*. 2008; Schneider *et al*. 2008) and to alleviate interference from atmospheric and soil 'noise' on vegetation indices under partial canopies in clear and turbid atmospheres without aerosol and ozone interference (Huete and Jackson 1988; Kaufman and Tanre 1992). Atmospheric indices have even been applied to counteract atmospheric effects in the use of NDVI in archaeological research (Agapiou *et al.* 2011).To the best of my knowledge there is no literature attempting to link the relationship between atmospheric indices and animal movements.

Moisture Indices

Ground measurements of soil moisture are time consuming, labour intensive and limited to specific locations consisting of a fraction of a meter below the soil surface and they cannot account for the heterogeneous spatial distribution of soil moisture (Weidong *et al.* 2003; Wang and Qu 2009). Remote sensing techniques using optical and thermal sensors provide a broad coverage at the required spatial resolutions (10 m to 100 m) for the quantification of soil moisture (Wang and Qu 2009) and they can create a comprehensive idea of soil moisture patterns across a landscape (Zeng *et al.* 2004). However they can only measure to a depth that includes the top few millimetres of surface moisture (Moran *et al.* 2004). Also, indices derived from optical and thermal bands are limited as their values can be distorted by clouds, vegetation cover and properties of soil reflectance such as texture, mineral and organic composition, incoming radiation and wind speed (Moran *et al.* 2004; Wang and Qu 2009). Active and passive microwave and radar sensors are able to penetrate cloud cover, vegetation cover and the soil to a depth of 5 cm, which is preferable to optical and thermal sensors (Western *et al.* 2002), but they have a very coarse spatial resolution of around 30 km and are distorted by surface roughness (Moran *et al.* 2004). Zeng *et al.* (2004) describe a soil moisture index that can be calculated from surface temperature and NDVI data, where surface temperature is measured from temperature emitted from the land surface and NDVI is determined from land surface reflectance. Together these variables can infer soil moisture by measuring the surface temperature at given NDVI values. The disadvantage of this method is that pixels of the most extreme conditions (totally wet vegetated pixels; totally wet bare soil pixels; totally dry vegetated pixels; and totally dry bare soil pixels), must be present in an image in order to calibrate the common conditions found within these boundaries (Kaleita *et al.* 2005). However, when the intention is to measure soil moisture in the context of animal distribution, soil moisture indices and indices of moisture within vegetation are transposable (Loyd, *pers. comm.* 2014) as both will effect animal resource selection because herbivores select for vegetation with higher water content (Besnard *et al.* 2013).

Indices of moisture within the vegetation are more straightforward to calculate and better represent what an animal might be selecting for; therefore only one of these types of indices will be used in this study. The Normalised Difference Water Index (NDWI) measures the bioavailable water in vegetation and can be used in place of a soil moisture index (Gao 1996; Jackson *et al.* 2004; Loyd, *pers. comm.* 2014). This is because it is sensitive to the liquid water content of canopies, which is directly affected by soil moisture (Gao 1996). Liquid water molecules in vegetation interact with incoming solar radiation and are less sensitive to the scattering effects of the atmosphere than NDVI (Gao 1996). NDWI continues to be sensitive to water content fluctuations in vegetation after NDVI has saturated (Jackson *et al.* 2004). The index does not saturate over open water; and is sensitive to soil moisture in fallow fields (low moisture), natural vegetation (moderate moisture) and irrigated fields (high moisture) (Gao 1996).

The soil moisture index NDWI has been linked to studies on soil moisture fluctuations that cause plant stress in drought (Gu *et al.* 2008; Horion *et al.* 2004), water mapping (Ji *et al.* 2009), monitoring live fuel moisture as an indicator of fire risk in savannas (Verbesselt et al. 2006), measuring liquid water content in vegetation canopies (Gao 1996; Jackson *et al.* 2004). Gu *et al*. (2008) found that plant biomass productivity could be measured more reliabily through the the ability of soil to retain moisture as indicated by NDWI, than through NDVI. As NDVI is used as a proxy for vegetation productivity and thus animal distribution, it could be argued that an indicator of soil moisture could enhance or improve the understanding of animal locations within a landscape.

Mineral indices

Soil provides ecosystem services that include nutrient cycling, primary production, physical support for plants and water availability (Palm *et al.* 2007). In order to understand the link between soil and ecosystem services, it is important to have information about the percentage of clay and mineralogy present in the soil. These properties determine the aggregation of soil particles, which influence nutrient supply and assimilation rates of water to the food web (Palm *et al.* 2007). This in turn affects the type of vegetation communities overlying the soil and thus the distribution of animals with regard to available forage in each community (McNaughton 1988). The use of a mineral index assists in describing soil properties (Dogan, 2009) and therefore the type of ecosystem processes operating within the landscape, which effect animal distribution (Palm *et al.* 2007).

Mineral indices can be derived from various multispectral and hyperspectral satellite data and from narrow bands within the visible, NIR and thermal infrared (TIR) spectral region. Remote sensing can identify various minerals, which create different spectral signatures from the soil surface (Escadafal and

Huete 1992) and nutrient availability can be defined from soil maps created from this data (Yoshino *et al.* 2012). Although hyperspectral imaging is superior for the purposes of mineral prospecting and mapping (Mulder *et al.* 2011); multispectral imaging can be used to assess mineral composites including ferrous minerals, iron oxide and clay minerals (Dogan 2009). Visible blue, visible red, NIR and TIR, all available from Landsat 8, can be used in different combinations to measure these minerals (Dogan 2009).

Animal distribution is linked to soil mineral content as essential minerals required by animals are attained through ingestion of plants (McNaughton 1988 and 1990; Vert *et al*. 2002; Lillesand *et al.* 2008; Ohyama 2010). However none of the above-mentioned studies employed remote sensing techniques or satellite indices, therefore the usefulness of mineral indices with regards to animal forage selection still remains to be tested. Mineral composite indices have been used to assess land cover change (Sarajlic 2012) and there are many studies done on mineral exploration using Landsat imagery in the field of geology (Hunt 1977; Bennet *et al*. 1993; Harris *et al.* 1998; Tangestani *et al*. 2004; Carranza and Hale 2002; Soe *et al*. 2005; Knepper 2012) and mining (Chica-Olmo *et al.* 2002; Pour and Hashim 2004), but I was unable to find literature linking mineral indices acquired by multispectral satellite imagery to animal distributions.

Landsat 8

Landsat 8 came online in May, 2013. It has on board a push-broom imager called Operational Land Imager (OLI), which is a moderate resolution multispectral instrument that replaces the ETM+ (Enhanced Thermal Mapper Plus), found on board Landsat 7. In addition it provides two unique new wave bands (Appendix I). The first being the coastal aerosol band (Band 1), which tracks airborne particles of dust and smoke (European Space Agency (ESA) 2013). This can be used to alleviate 'noise' created by the scattering of these aerosols in the atmosphere and thus producing clearer images. The second new band on Landsat 8 is a short wave infrared band (Band 9) that is capable of detecting high altitude cirrus clouds that cannot be seen on other spectral bands. Pixels under these undetected clouds may be skewed due to the presence of these clouds, and image analysts can now correct for this error on the final image (ESA 2013).

The OLI does not include thermal infrared bands, so a Thermal Infrared Sensor (TIRS) is also incorporated in the payload of Landsat 8. This provides two infrared bands, which are needed to offer continuity for data supplied by previous Landsat missions; such as the thermal infrared band (TIR Band 6) on Landsat 7 ETM+ (ESA 2013). Included in the TIRS sensor on Landsat 8 is an additional unique TIR band that measures heat emitted by the Earth (Loyd 2013). Data from the two infrared bands onboard Landsat 8 are merged into a single multispectral product corrected for atmospheric noise (ESA 2013). This allows estimates of canopy evapotranspiration (Serbin *et al.* No Date), soil moisture, thermal mapping, and fire monitoring (ESA 2013).

The temporal resolution of the Landsat platform is 16 days (Loyd 2013). The spatial resolution of the visible, thermal infrared and shortwave infrared bands is 30 m. There is also a panchromatic band (Band 8) with a spatial resolution of 15 m and the two TIR bands have a spatial resolution of 100 m (Loyd 2013) (Appendix I). It is expected that due to the fine spatial resolution of Landsat 8, the scale for greenness will be improved and will give a clearer idea per pixel than MODIS, as to what part of the greenness value constitutes grass, tree or shrub cover (Loyd 2013).

Study area

Kgaswane Mountain Reserve (KMR) (25 43ºS, 27 11ºE) is a 5000 ha game reserve located in the Magaliesberg Mountain Range on the southern edge of Rustenburg, Northwest Province (Figure 1.1). It is described as having moderate to high relief, with altitudes ranging between 1250 m above sea level in the low-lying areas, to 1600 m on the western summits (Coetzee 1975). It comprises a high-lying grassland plateau, which includes a wetland forming the headwaters of a catchment area containing the source of the Hex River and two of its tributaries (Ololade 2012). From the summit plateau, the reserve drops to the base of the mountain range and consists of valleys and low-lying woody plains. The slopes ascending to the summit contain deep forested ravines (Coetzee 1975).

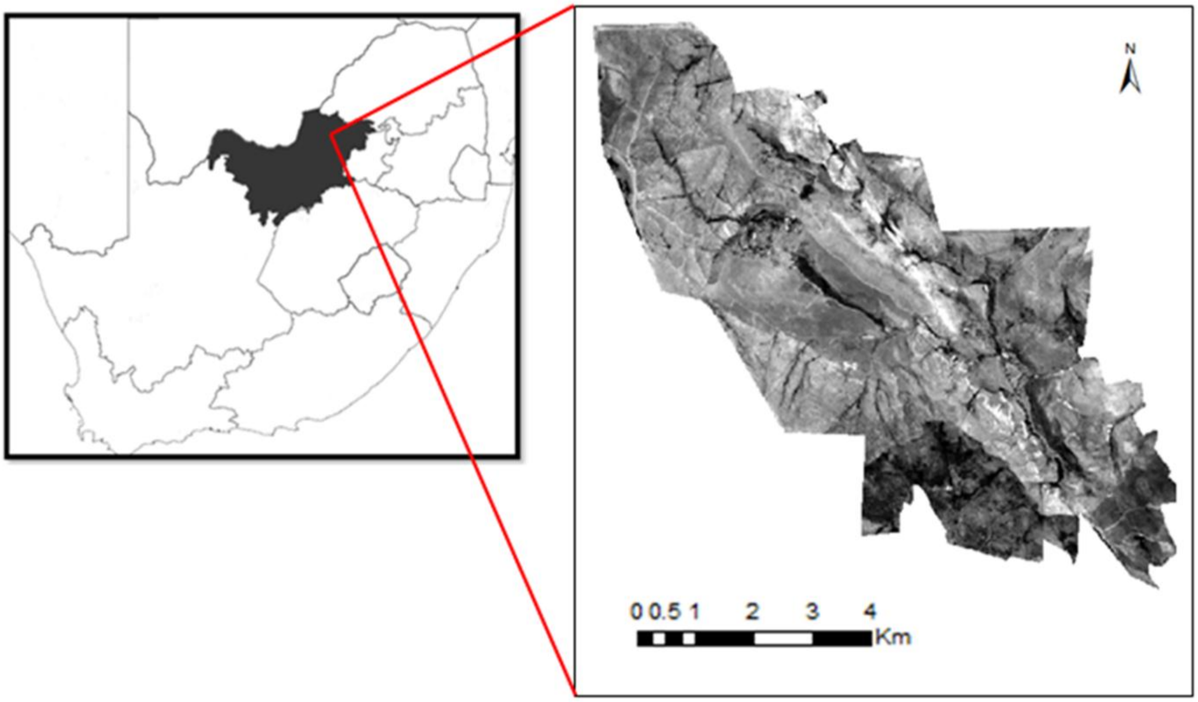

Figure 1.1 Map of Kgaswane Mountain Reserve (25 43ºS, 27 11ºE) situated in the Northwest Province of South Africa at the northwestern end of the Magaliesberg Mountain Range.

The plateau is described as infertile sourveld and the low-lying area at the base of the mountains is described as bushveld (Acocks 1988). Nel (2000) classified the vegetation component of KMR, based on abiotic factors such as soil depth, clay content, soil moisture and geology. Nel (2000) identified a total of 611 plant species within 51 different vegetation communities. Some vegetation communities were further categorised into sub-communities, depending on variations in the most conspicuous plant species (Figure 1.2). Nel (2000) then combined these vegetation communities into four main homogenous units. These units are:

Selaginella dregei - *Oldenlandia herbacea* open shrub land found on shallow Mispah and Glenrosa soil forms on quartzite rock of high lying slopes.

Becium obovatum - *Elionurus muticus* tall grassland covering medium Glensrosa to deep Hutton soil forms found either on quartz bedrock in the central basin or norite rock on the foot slopes of the mountains.

Ziziphus mucronata - *Rhus leptodictya* closed woodlands on norite diabase in low-lying slopes and eastern valleys, with medium to deep Glenrosa soil forms on the slopes to deep alluvial soils in the valleys.

Pteridium aquilinum - *Miscanthus junceus* moist grasslands on deep, black Willowbrook and Kroonstad soil forms in the wetland and on deep Hutton soils alongside streams and drainage lines in the southern part of the central basin.

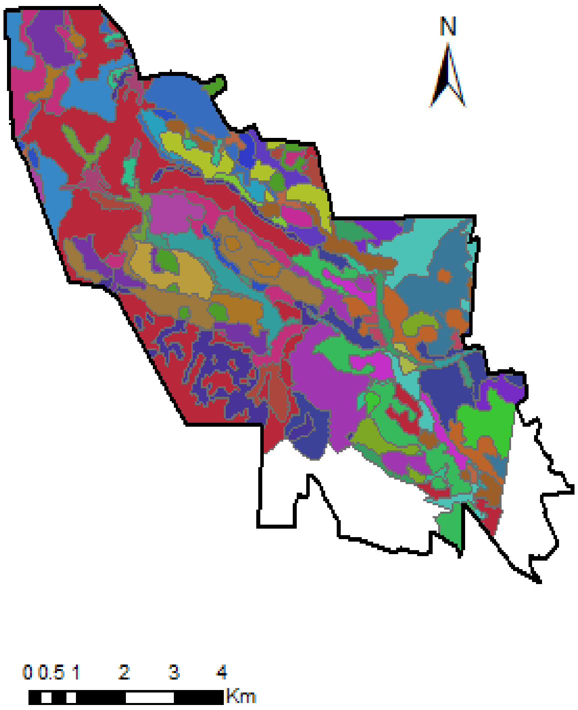

Figure 1.2 Vegetation shape-file of Kgaswane Mountain Reserve (The black outline represents the present boundary).

Key

🟪 Aloe greatheadii- Themeda triandra Tall Open Woodland
🟩 Aristida junciforms- Arundinella Tall Closed Grassland
🟩 Aristida transvaalensis- Bulbostylis burchellii Tall Sparse Shrub land
🟦 Asparagus krebsianus- Senecio venosus High Open Shrub land
🟪 Asparagus virgata- Celtis africana Tall Closed Woodland
🟪 Becium obovatum- Protea caffra Tall Closed Woodland
🟦 Blumea alata- Parinari capensis sub-community
🟩 Brachylaena rotundata- Englerophytum magalismontanum High Open
🟩 Burkea africana- Setaria sphacelata Tall Open Woodland
🟪 Ceterach cordatum- Tristachya leucotrix Tall Sparse Shrub land
🟦 Cheilanthes viridus- Combretum molle Short Open Woodland
🟦 Croton grastissimus- Combretum molle Short Open Woodland
🟩 Cryptolepis oblongifolia- Loudetia simplex Tall Sparse Woodland
🟪 Digitaria eriantha- Lippia javanica Tall Closed Woodland
🟪 Diheteropogon amplectens- Ficinia filiformis Short Closed Woodland
🟥 Diospyros lycioides- Cymbopogon validus Tall Sparse Shrub land
🟫 Euclea crispa- Panicum maximum Tall Closed Woodland
🟩 Faurea siligna- Cyperus sphaerosermus Short Open Woodland
🟦 Heteropogon contortus- Faurea saligna Tall Open Woodland
🟪 Heteropogon contortus- Trachypogon spicatus Tall Open Woodland
🟩 Hyparrhenia hirta- Bidens pilosa Short Sparse Woodland
🟦 Indigofera burkeana- Rhynchosia totta Short Closed Woodland
🟫 Indigofera comosa- Schizachyrium sanguineum Tall Closed Grassland
🟥 Lopholaena coriifolia- Lapeirousia sandersonii Short Open Grassland
🟥 Loudetia flavida- Tristachys biseriata Tall Closed Shrub land
🟧 Mimussops zeyheri- Hypoetes forskaoli Tall Forest
🟩 Olea europaea- Grewia occidentalis Tall Closed Woodland
🟨 Plexipus hederaceus- Cymbopogon excavatus Tall Closed Grassland
🟧 Protea gaguedi- Monocymbium ceresiiforme Short Open Shrub land
🟩 Pteridium aquilinum- Miscanthus junceus Tall Closed Grassland
🟦 Ruellia cordata- Senecio venosus Tall sparse Woodland
🟩 Ruellia patula- Melinus nerviglumis Short Open Woodland
🟩 Senecio venosus- Heteropogon contortus Tall Closed Woodland
🟧 Setaria sphacelata- Themeda trianda Tall Closed Woodland
🟥 Tagetes minuta- Commelina africana Sparse Open Woodland
🟦 Themeda triandra- Eragrostis racemosa Short Open Grassland
🟩 Trachypogon spicatus- Bulbostylis burchellii Short Sparse Woodland
🟥 Trachypogon spicatus- Sphenostylis augustifolia Tall Closed Grassland

The area is situated in the summer rainfall climatic zone, with rain falling mostly between November and March. This marks a distinct wet and dry season for the region. The total annual rainfall for the study period (June 2013 to September 2014) was 632.1 mm, which was above the long term average of 589 mm for the period of 1980 – 2014; with 628.6 mm falling between October 2013 and March 2014 (Kgaswane Mountain Reserve Weather Station). Temperatures average at 16.8˚C to 30˚C in summer and 6.7˚C and 21.7˚C in winter (Parrini 2006). Light frost occurs from June to August on the plateau, but does not occur in the low lying valleys (Nel 2000), and the average weekly temperature is higher in the low lying areas than on the plateau and crests of the north-facing slopes (Van Vuuren and van der Schijff 1970 in Nel 2000).

The Magaliesberg Mountain Range, where KMR is situated, is an extended ridge of inclined quartzite named the Magaliesberg Formation, consisting of dolomite, shale and quartzite, known as the Pretoria Group; a subset of the Transvaal Supergroup (Norman and Whitfield 2006; McCarthy 2009). The reason for the inclined gradient of the range is the intrusion of the Bushveld Igneous Complex, which depressed the formation at its base and caused it to tilt (Norman and Whitfield 2006). The Bushveld Igneous Complex was formed by a continual infiltration of iron and magnesium rich magma into a shallow, sub-surface chamber, resulting in cooling processes occurring at different rates and temperatures (Coffin and Eldholm 1994). This formed various minerals, which precipitated as the magma cooled (Ololade 2012); hence the development of the nearby mining town of Rustenburg.

The low-lying area of KMR lies on the Bushveld Igneous Complex, which has three divisions; but the one occurring in KMR is the Rustenburg Layered Suite, which consists mainly of iron-rich Kolobeng Norite (McCarthy 2009). Due to the fast cooling processes of the intrusion, part of the quartzite from the older Transvaal Sequence was assimilated into the norite rocks and now these rocks also contain quartz in some areas of the reserve (Norman and Whitfield 2006). Although norite mainly occurs in the low lands, there are also pockets of it occurring on the plateau (Nel 2000).

The soils on the plateau of KMR, originating from the underlying geological strata of the Transvaal Sequence, are mainly unproductive, acidic quartzite sandstone (Acocks 1988).The iron rich soils of the lowlands range from sandy to clayey norite, depending on their position on the catena (MacVicar *et al.* 1977; Nel 2000) and are superimposed on the Kolobeng Norite parent material of the Bushveld Igneous Complex (MacVicar *et al.* 1977).

A large portion of KMR soils consists of one family of the Mispah Form (Nel 2000). These are shallow soils with a coarse gravel texture underlain by hard quartz rock (MacVicar *et al.* 1991). Another common soil form found in the reserve is the Glenrosa Form; medium to deep soils that form a transition between the shallow Mispah soils on the summits and the deep soils in the vlei and in the lowlands (Nel 2000). Glenrosa soils have been classified depending on the geological template and the position of the soils in the catena (MacVicar *et al.* 1977). Soils on the higher slopes will tend to be sandier and those at the foot of the slope will accumulate clay (Nel 2000; Khan *et al.* 2013). In KMR there are five different series of the Hutton Form (Nel 2000); which are deep, well-differentiated soils separated by the proportion of sand or clay found within the B Horizon, and the amount of leaching that occurs (MacVicar *et al.* 1977). The Hutton Form soils with the highest percentage of sand are found in higher areas underlain by quartzite. The soils with the highest clay content are found in the low lying areas that are underlain by norite (Nel 2000).

The reserve contains a range of herbivore species, which includes zebra, blesbok (*Damaliscus pygargus phillipsi*), common reedbuck (*Redunca arundimun*), mountain reedbuck (*Redunca fulvorufula*), red hartebeest (*Alcelaphus caama*), impala, klipspringer, kudu, oribi (*Ourebia ourebi*), springbok (*Antidorcas marsupialis*), waterbuck (*Kobus ellipsiprymnus*), roan antelope, sable antelope and eland. There are two herds of sable antelope in KMR; one situated on the grassland plateau on the summit of the Magaliesberg mountain range and the other in the low-lying woodlands at the base of the range. The eland population usually forms one big herd during the wet season and splits into smaller units during the dry season. At the time of the study the eland population amounted to about 50 individuals and the sable population to about 51 individuals (Tshengkeng 2014).

Study species

Sable antelope *(Hippotragus niger)*

Sable antelope are medium-sized, water dependent grazing ruminants belonging to the Bovidae family, occurring in the northern and northeastern parts of the southern African sub-region, in dry grasslands and open woodlands (Smithers 1986; Estes 1991; Carruthers 1997). Both male and female have white underbellies, but the adult males are black on the upper body and the females are dark brown to black, while the young are russet coloured (Smithers 1986). They are gregarious, normally occurring in herds of up to 25 individuals (Wilson and Hirst 1977) comprising a dominant adult bull, adult cows, juvenile females, males younger than two years, and calves (Smithers 1986). Both male and female become reproductively active at two years of age; with females producing their first calves at three years (Smithers 1986). Young males, although capable of reproduction, are prevented from mating by dominant bulls and may only be capable of establishing a territory and mating at six years of age (Capon *et al,* 2013). Breeding herds are controlled by an alpha female who initiates activities such as foraging, seeking water, moving and fleeing predators (Wilson and Hirst 1977).

Sable antelope prefer open woody habitats, utilising more open grasslands in the wet season and moving to open woodland in the dry season when resources are limited (Jarman 1972; Wilson and Hirst 1977; Parrini 2006; Owen-Smith *et al*. 2012). They are low density selective grazers, preferring medium to tall grass swards that suits their narrow dental arcade (Traill 2004). Sable antelope are reported to eat grasses such as *Chrysopogon serrulatus*, *Panicum maximum, Heteropogon contortus, Themeda triandra, Hyperthelia dissoluta, Trachypogon spicatus*, *Setaria sphacelata* and *Loudetia simplex,* (Magome *et al*. 2008; Macandza 2009; Le Roux 2010; Mokoena 2012). During adverse conditions, they are able to diversify their diet to less favourable grass species such as *Panicum deustum, Schmidtia pappaphoroides* and *Ischaemum afrum* in Kruger National Park; where they also tolerated *Urochloa mosambicensis* and

Digitaria eriantha during the early dry season, while this grass was still green (Macandza 2009). Parrini (2006) observed that in KMR sable antelope preferred grazing *T. triandra, P. maximum*, *Hyparrhenia hirta, Andropogon schirensis* and *H. contortus* in the wet season; and *T. triandra, P. maximum*, *H. contortus, Dihetreropogon amplectans* and *Digitaria* spp. in the dry season. During the dry season sable antelope also tolerated less palatable browner and stemmier grass, such as *H. hirta* and *A. schirensis* (Parrini 2006). These grass species were accepted, especially if they still retained remnants of green foliage (Parrini 2006; Owen-Smith *et al.*, 2013); where the animals ate the green leaves on the stems rather than the basal tufts (Grobler 1981; Parrini 2006; Le Roux 2010). Therefore sable antelope are tolerant of tall grass species with less forage value (Parrini 2006; Le Roux 2010) and are also able to adjust their preferred grazing height as resources became more limited (Parrini 2006; Macandza 2009). In fact they are often found grazing in the green flush produced after a burn, despite the short grass available there (Magome *et al.* 2008; Parrini and Owen-Smith 2010). During the dry season in burnt areas in KMR, species that were eaten included *T. spicatus, Tristachya leucothrix, Schizachyrium sanguineum, Setaria* spp, *Eragrostis* spp and *Cymbopogon validus* (Parrini 2006); species that are otherwise avoided.

Eland (*Tragelaphus oryx*)

Eland is the largest southern African ruminant belonging to the Bovidae family (Estes 1991). The eland is a water-independent species, drinking opportunistically, but able to survive from the moisture within the leaves of plants (Smithers 1986; Rudee 2011). If water is inaccessible, eland conserve water through a number of physiological adaptations such as raising their daily body temperature, which causes rapid cooling at night thus preventing evaporative water loss (Estes 1991). They also concentrate their urine and feces and lower their metabolic rate (Estes 1991). Behaviourally they adapt to less water by sheltering in shady places during the day and grazing at night and in the early morning (Estes 1991).

Both sexes are fawn-coloured, with prime males turning grey (Carruthers 1997). Both male and female have horns; the male horns are shorter, thicker and more spiraled at the base than the female horns (Smithers 1986). Calving occurs throughout the year, but mainly in the early wet season when resources are most plentiful (Pappas 2002; Rudee 2011). Due to their gregarious and non-territorial nature, eland form large aggregations in the wet season (Smithers 1986; Hillman 1987; Hofmann, 1989; Estes 1991) and in the dry season they split into smaller herds of up to about 50 members, depending on the size of the area and resource availability (Hillman 1987; Carruthers 1997). Herds of females and juveniles usually range further than bachelor herds, but both herds decrease their range in the dry season (Hillman 1988). In semi-arid shrub-lands, eland were reported using plateau habitats in the wet season and moving to valleys and slopes in the dry season, where more trees could be found (Watson and Owen-Smith 2000).

Due to their large body size, eland have a high food requirement, which makes them unable to forage too selectively (Hofmann 1989). Because they are ruminants they also have a high metabolic rate and need a high protein diet (Pappas 2002) and are described as mixed feeders (Lamprey 1963; Hofmann 1989; Estes 1991). They have been observed eating low-fiber plant species such as forbs and leafy shoots with higher protein content (Field 1975; Hofmann 1989; Watson and Owen-Smith 2000). In order to adapt to this feeding regime, they are considered semi-nomadic (Underwood 1981); utilising a wide diversity of plants and habitats ranging from moist savannas to semi-deserts (Jarman 1974; Pienaar 1974; Estes 1991). During the wet season, when grass is green and plentiful, eland are grazers; but change to browse in the dry season as the nutritious quality of grass becomes limiting (Buys and Dott 1991; Estes 1991; Wallington *et al*. 2007), and woody plants still retain high protein content (Field 1975).

A number of studies have been done on the foraging preferences of eland during both the wet and dry seasons in Kenya (Nge'the and Box, 1976); in the Mountain Zebra National Park, South Africa (Watson and Owen-Smith 2000); in Suikerbosrand Game Reserve, South Africa (Wallington *et al.* 2007); and in KMR (D'Ammando *et al.* 2014). Collectively it was observed that trees and shrubs browsed by eland in the dry season were *Acacia brevispica, Acacia tortillis, Acacia senegalensis,* (Pappas 2002; Nge'the and Box 1976), *Combretum molle, Combretum zeyheri* (Pappas 2002; Nge'the and Box 1976; D'Ammando *et al.* 2014), *Commiphora africana, Commiphora riperia* (Pappas 2002; Nge'the and Box 1976), *Grewia bicolor*, *Grewia vilosa, Grewia occidentalis* (Pappas 2002; Nge'the and Box 1976; Watson and Owen-Smith 2000), *Searsia erosa* (formerly *Rhus erosa*), *Searsia pyroides* (formerly *Rhus pyroides*), *Searsia leptodictya* (formerly *Rhus leptodictya*) (Pappas 2002; Watson and Owen-Smith 2000; Wallington *et al.* 2007), *Ziziphus mucronata* (Pappas 2002; D'Ammando *et al.* 2014), *Dichrostachys cinerea, Sida ovalis, Dalbergia melanoxylon* and *Disperma kilimandscharia,* (Nge'the and Box 1976), *Mundulea sericea, Leucosidea sericea, Crysanthemoides monilifera, Athrixia rosmarifolius, Kiggelaria africana, Halleria lucida, Dombeya rotundifolia, Vanguera infausta, Withania somnifera, Tarchonanthus camphoatu,* and *Otholobium polystrictum* (Wallington *et al.* 2007), *Lippia javanica,* (Wallington *et al.* 2007; D'Ammando *et al.* 2014), *Pentzia sphaerocephala* (Watson and Owen-Smith 2000), *Ehretia rigida*, (D'Ammando *et al.* 2014). Dwarf shrubs eaten by eland were *Helichrysum dregeanum* (Watson and Owen-Smith 2000; D'Ammando *et al.* 2014), *Walafrida genicolata* and *Felicia muricata* (Watson and Owen-Smith 2000) and an unidentified *Solanum* species (D'Ammando *et al.* 2014).

Throughout the year eland utilised the forbs *Bidens pilosa* and *Tagestes minuta* (Pappas 2002; Nge'the and Box 1976; Wallington *et al.* 2007), *Hibiscus calyphyllus* (Wallington *et al.* 2007), *Dolochos molasanus, Aerva persica* and unidentified species from the genera *Cucumis* and *Desmodium* (Nge'the and Box 1976); unidentified species from the genera *Acanthospermum* and *Tarchonanthus* (Pappas 2002) and unidentified species from the genera *Plecanthrus* and *Vernonia* (D'Ammando *et al.* 2014). During the wet season eland grazed on the grasses *T. triandra, Digitaria milanjiana* and *D. eriantha* (Nge'the and Box 1976; Watson and Owen-Smith 2000), *Eustachys paspaloides, Bothriochloa insculpta, P. maximum, P. deustum, Cynodon dactylon, Chloris roxburghiana* and *Cenchrus ciliaris* (Nge'the and Box 1976) and *Cymbopogon plurinodis* (Watson and Owen-Smith 2000). However D'Ammando *et al.* (2014) studied eland diet in the dry season in KMR and found that eland in the reserve were mostly utilising *T. leucotryx,* which was the greenest grass species available.

Dissertation structure

The study is divided into four chapters:

Chapter 1 is a general introduction to the study topics and a detailed description of the study area and of the study species; to provide information that will be used to interpret results for Chapter 2 and 3, which are the two data chapters. Because the study area and study species are described in detail in this chapter, they will not be described in Chapter 2 and 3, in order to avoid unnecessary repetitions. I will therefore refer to Chapter 1 instead. Each chapter has its own reference list, so some repetition is unavoidable.

Chapter 2 provides a detailed description of the landscape characteristics associated with sable antelope and eland locations on the days of the satellite images, to help interpret the outcomes of the models discussed in Chapter 3. The main objectives for Chapter 2 are to assess the landscape level characteristics where the animals were located with regards to: (1) vegetation communities used vs. vegetation communities available; (2) use of burned areas; (3) vegetation communities characterising the used burnt areas; (4) geology and soil type underlying the used vegetation communities. As KMR is a small reserve, distance to drinking water is not an issue and so surface water has not been considered as a variable limiting animal locations.

Chapter 3 deals with the main purpose of this study, which is to explore whether there are other satellite indices apart from Normalised Difference Vegetation Index (NDVI) that may improve understanding of animal locations within the landscape. These indices or combinations of indices are derived from Landsat 8 bands. The indices tested are SAVI (Soil Adjusted Vegetation Index), VARIgreen (Visible Atmospherically Resistant Index), GARI (Green Atmospherically Resistant Index), NDWI (Normalised Difference Water Index) and mineral composite indices that assess the different spectral signatures of clay minerals, ferrous minerals, and iron oxide. The main objectives of Chapter 3 are: (1) assess the ability of NDVI and other indices derived from Landsat 8 to describe herbivore locations within the landscape; (2) determine whether similar indices would be consistent for different habitats and different herbivore species, by comparing two sable herds occurring in different areas and one sable and one eland herd occurring in the same area.

Chapter 4 is the conclusive chapter in which I integrate all findings, discuss the limitations of the study and suggest further avenues of research.

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CHAPTER 2 CONTEXTUAL DESCRIPTION OF THE VEGETATION COMMUNITIES, GEOLOGY, SOIL AND BURN STATUS ASSOCIATED WITH THE LOCATIONS OF THE STUDY ANIMALS IN KGASWANE MOUNTAIN RESERVE

Introduction

In a grassland or savanna, isolated patches of high quality forage are found among abundant, low quality vegetation (Senft *et al.* 1987). This is due to erratic rainfall patterns, which influence where nutritious grasses will be found within the landscape (Scholes 1990). Grass is always dependent on rain induced soil moisture to catalyse regrowth or a green flush (Prins and Loth 1988; Shackleton 1999). Therefore at the beginning of the wet season, new growth occurs throughout the grassland and contains high levels of protein, but low biomass (Bell 1971; Fryxell 1991). As the dry season advances, the grass grows taller, accumulates structural carbohydrates and secondary defence mechanisms, and replaces protein content for increased fibrous biomass (Owen-Smith 1982; Owen-Smith 2002).

In the dry season herbivores have an increasingly narrow choice of resources and must either travel further to find good quality food, or eat larger quantities of low quality forage (Bailey *et al.* 1998). In these circumstances, they may change their foraging preferences to include less palatable vegetation species (Bailey *et al.* 1996). This behaviour is determined by the foraging strategy adopted by each species of herbivore, depending on their physiological constitution, which includes factors such as body size, muzzle size and type of digestive system (Owen-Smith 1982). For example ruminants need high quality forage as they are limited to a longer gut-retention time than non-ruminants, who can eat greater quantities of fibrous food (Illius and Gordon 1992). Therefore ruminants need to seek out food that is high in protein and low in fibre even if it means shifting their range during the dry season (Traill 2003), or using areas where green vegetation is still found (Parinni and Owen-Smith 2010).

The tree and shrub component of a grassland or savanna contributes towards patches of high quality forage within the landscape (Borchert 1999). The roots of trees are able to access water and nutrients at depths unavailable to grass, so that grass growing beneath tree canopies can take up more water and nutrients from the upper soil layers than grass growing in areas where trees are absent (Scholes 1990; Ludwig *et al*. 2003). Also leaf fall from trees increases the amount of organic matter and decomposition beneath the canopy, adding to soil fertility (Sutton *et al.* 2002). For example in the dry season, sable antelope (*Hippotragus niger*) move from grasslands to open woodlands, where the grasses benefit from the sub-canopy soil fertility (Jarman 1972; Wilson and Hirst 1977).

When deciduous trees senesce, there is usually a presence of evergreen species that continue to be used as browse throughout the dry season and generally trees can sustain higher protein content for a longer duration than grasses (Field 1975). In some species, tree flush is initiated by temperature and photoperiod (Scholes and Archer 1997; Archibald and Scholes 2007), which may occur before the first rains conclude the dry season; whereas other tree species depend on rain to begin their flush (Borchert 1994), which means that during the dry season, browsers have more access to sustainable forage that grazers.

In the dry season browsers will accept forage from species that are considered unpalatable in the wet season, as long as the protein level in the new leaves is higher than the tannin concentration (Cooper *et al.* 1988). For example mixed feeders such as eland (*Tragelaphus oryx*), can switch from grazing in the wet season to browsing in the dry season when resources are limited (Buys and Dott 1991) and their food preference depends on the availability of what is still green (Nge'the and Box 1976; D'ammando *et al.* 2014). Kudu (*Tragelaphus strepiceros*), a pure browser, also utilises the greenest available leaves regardless of tannin concentrations as long as their diet is diverse enough to incorporate enough protein to counteract the varying amounts of tannins found in different browse species (Hooimeijer *et al.* 2005).

Nutrient cycles in grassland and savanna biomes are also affected by fire, which cause patches of high quality vegetation growth across the landscape through time and space (Fuhlendorf *et al.* 2008). Forage quality in the post-burn flush is caused by new growth of vegetation, which increases leaf - stem ratios, so the flush contains young leaves with higher protein levels but lower quantities of biomass compared to unburnt areas (Van der Vijver *et al*. 1999; Hassan *et al*. 2007; Allred *et al*. 2011). Therefore herbivores can be highly attracted to the green flush (Fuhlendorf and Engel, 2004). Tomor and Owen-Smith (2002) compared the use of burnt grassland by tsessebe (*Damaliscus lunatus*), roan antelope (*Hippotragus equinus),* blue wildebeest (*Connochaetes taurinus*), and Burchell's zebra (*Equus quagga*) in Nylsvley Nature Reserve. They found that all four species made use of the burnt areas but in differing amounts; with tsessebe making the least use, roan using partially burnt edges, and wildebeest and zebra using the entire burnt area, with zebra dominating the total spatial range of the burn. They concluded that the use of a burn depends on species-specific dietary requirements, behaviour, and inter-specific competition. This was validated by Gureja and Owen-Smith (2002) in the Madrid Game Ranch near Klaserie, where they found that roan antelope, tsessebe, Lichtenstein's hartebeest (*Alcelaphus lichtensteini*), sable antelope, and zebra made differing use of the burnt areas. Roan, tsessebe and zebra consistently grazed within the burns; roan preferring taller grass species under a canopy cover; and sable were mostly absent from the burn. Roan and hartebeest preferred lowlands and tsessebe, sable and zebra were more comfortable in the mid-slope to upland regions. Therefore the use of the burn depended on the topographical position of the burnt area within the landscape and the physiological characteristics of each animal species, which dictated forage preferences of grass species within the flush (Gureja and Owen-Smith 2002). In contrast, during the dry season in Kgaswane Mountain Reserve (KMR), sable antelope spent most of the time grazing in post-burn flushes with suitable vegetation regrowth, or even in the previous year's burnt areas (Parrini and Owen-Smith 2010).

Soils and the underlying geology are a vital component of the ecology of grassland and savannas, as they hold minerals and water available to plant roots; influencing the growth of plants and their distribution in the landscape (Lobell and Asner 2002; Western *et al.* 2002; Wang and Qu 2009). The geological template is the parent material from which the overlying soil forms originate (Strahler and Strahler 1973). Along with other variables, soil forms affect the type of plant communities growing in them (Palm *et al.* 2007). This is because soils hold nutrients derived from the bedrock, which effect plant mineral content (Strahler and Strahler 1973). This in turn impacts resource selection and the distribution of herbivores, as they obtain minerals indirectly from soil via plants and will select grazing areas where essential trace minerals are found (McNaughton 1988). In the dry season soil moisture declines and only strips of green forage remain around drainage lines and in bottomlands and only wetlands remain saturated (Anderson and Kneale 1980). Some soil types, such as clay soils, have a high capacity for retaining soil moisture and provide an excellent source of mineral nutrients for plants throughout the dry season (Scoones 1995; Dogan 2009).

The aim of this chapter is to explore the characteristics associated with the locations of the study animals (two sable herds and one eland herd) in terms of vegetation communities, burn status, geology, and soil type; in order to provide a background to interpret the relationships between locations and remote sensing indices that will be analysed in Chapter 3. The objectives are to evaluate the characteristics of the landscape where the animals were located with regards to: (1) vegetation communities used vs. vegetation communities available; (2) use of burned areas; (3) vegetation communities characterising the used burnt areas; (4) geology and soil type underlying the used vegetation communities.

I expect both sable and eland to concentrate in vegetation communities with suitable foraging species for them. The sable antelope will preferentially be found in open woody vegetation communities and burnt areas in the dry season, while eland, mainly browsing in the dry season (Field 1975), should be frequently found in closed woodland communities, and not necessarily in burnt areas. I also expect the soil and geology underlying different vegetation communities such as grassland, open or closed woodland to differ depending on the clay fraction and the topographical position of the vegetation community in the landscape.

Methods

Two female sable antelope from two separate herds (from now on called ‘vlei’ herd and ‘woodland’ herd respectively) and one female eland were fitted with satellite GPS collars (Africa Wildlife Tracking AWT: http://www.awt.co.za) in June 2012. The sable collars were fitted in 2012 as part of North Wests Parks Board monitoring programme and made available to us and the eland collar in 2013 (Wits Animal Ethics clearance: 2014/14/04). These collars supplied data of the animal’s location at hourly intervals for sable antelope, and at four hourly intervals for eland. Each collar recorded date, time of day, latitude and longitude coordinates, temperature, altitude, and speed and direction of animal movement. The sable collars recorded data from 6/1/2012 until 7/4/2013, when they were replaced by new collars, which recorded data until the end of the study period (4/9/2014). The eland collar provided data from 15/7/2013 to 4/9/2014.

I first identified the area of the reserve that was available to each of the three herds. It is known that the two sable antelope herds do not use overlapping ranges (Parrini 2006). This is confirmed by the present data, and hence the whole reserve is not available to each herd. Therefore I defined the area available to each herd as the 100% multiple convex polygon (MCP) including all the GPS locations for the period 2012 – 2014. Apart from using all available location points in the entire data set to build the MCPs, I only used data from 2013 to 2014 for the study as it was focussed on the dry season of this period.

To determine the vegetation communities, burn status, geology, and soil at the locations used by sable antelope and eland, I did not use all the available locations, but only the used locations from the days coinciding with the satellite images (Appendix II). The reason for doing this is that the aim of this chapter is to provide supportive information to help interpret the results of Chapter 3, and is not a resource selection study in its own right.

GPS locations and vegetation communities

Nel (2000) classified the vegetation components of KMR, based on an analysis of associated abiotic factors, in 51 different vegetation communities, and combined them into four main homogenous units. However, these units were regarded as too broad for this study, so the level of the 51 plant communities was used. I only focused on those communities that were actually used or non-used but available within each herd’s total home range. This accounts for a total of 38 vegetation communities, 32 of which were available (i.e. falling within their 100% MCP) to the sable vlei herd, 29 to the sable woodland herd and 30 to the eland herd. For each community I listed the occurring grass, shrub, and tree species that are suitable forage for sable and eland according to the literature review in Chapter 1.

Vegetation and burnt area shapefiles for 2013 and 2014 were acquired from the Northwest Parks and Tourism Board. I obtained information on the geology and soil characteristics of the areas available to the three herds from a geology and soil map adapted from Nel (2000). Using ArcGIS (Esri ® ArcMap ™) referencing tools, I geo-referenced these maps and imported them into ArcgGIS 10.2.

In ArcGIS 10.2, I overlaid the location points of all three herds onto the vegetation shapefile and I extracted the vegetation community at each location point. I then recorded the number of times each herd occurred in each plant community. I described these features in association with the non-used vegetation communities that occurred in each herd's home range by overlaying each herd's 100% MCP onto the vegetation shapefile using spatial analysis tools in ArcGIS 10.2.

GPS locations and burnt areas

Similarly, I overlaid the locations of all three herds on the burn areas shapefiles for 2013 and 2014, also acquired from the Northwest Parks and Tourism Board. Furthermore I superimposed the burnt area shapefiles onto the vegetation shapefile to identify the vegetation communities affected by the fires and to highlight any possible relationship between the use of burnt areas and the selection of vegetation communities. I then recorded the number of times each herd occurred in each burnt area.

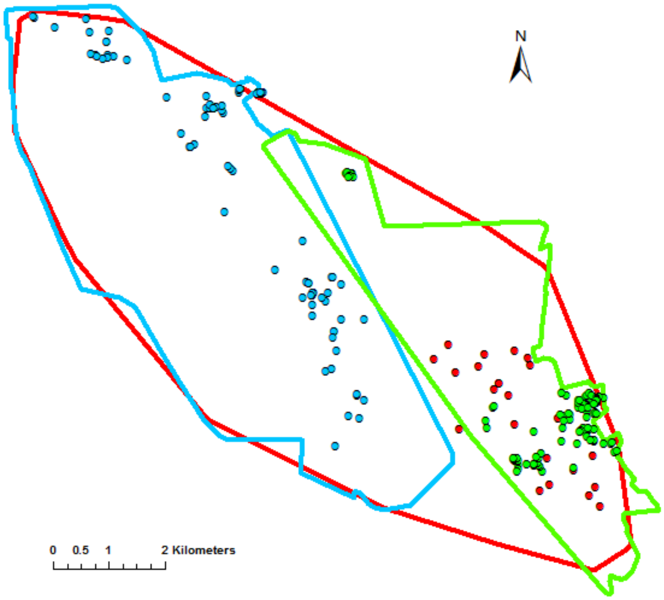
GPS locations, geological substrate and soil forms

I obtained information on the geology and soil characteristics of the areas available to the three herds from a geology and soil map adapted from Nel (2000). Using ArcGIS (Esri ® ArcMap ™) referencing tools, I geo-referenced these maps and imported them into ArcgGIS 10.2. I then overlaid the locations of all three herds onto the soil and geology maps in order to define the soil and geology characteristics at used locations.

Results

Identifying the area available to the sable and eland herds

I used all the GPS locations available for sable antelope from 2012 to 2014, and the eland locations from 2013 to 2014 to create multiple convex polygons (MCPs) to define the area available to each herd (Figure 2.1). It was confirmed that the sable antelope consisted of two separate herds; the vlei herd occupying the high-lying plateau area, including the vlei, which gave the herd its name and the woodland herd found in the low wooded valleys at the base of the Magaliesberg range. The herds did not use all of the area available to them during the dry season of 2013 and 2014 (Figure 2.1). The vlei herd ranged through the foothills in the northern part of the plateau, along the northeastern ridge, in the central basin and the southeastern areas of the plateau and avoided the eastern side of the reserve. The woodland herd was located within the southeastern portion of their range and did not move onto the plateau.



MCP boundary	GPS locations	Herd
🟦	🔵	Sable vlei
🟩	🟢	Sable woodland
🟥	🔴	Eland

Figure 2.1 Multiple Convex Polygon (MCP) 100% home ranges for the sable antelope vlei herd, sable antelope woodland herd and eland herd in Kgaswane Mountain Reserve based on all locations for 2013 and 2014 and GPS locations corresponding to days with Landsat 8 images.

Eland are generalist feeders and they tend to form large groups in the wet season when resources are plentiful. This is reflected in the fact that their MCP covers the entire reserve (Figure 2.1). During the dry season eland split into smaller herds. The female eland that was collared remained with the herd that occupied the low woodland valleys in the same region as the sable woodland herd (Figure 2.1).

GPS locations and vegetation communities

The most frequently used vegetation communities by the vlei herd were the *Burkea africana* - *Setaria sphacelata* tall open woodland and *Croton gratissimus* - *Combretum molle* short open grassland (Appendix III). This herd also used *Lopholaena coriifolia* - *Lapeirousia sandersonii* short open grassland.

All the vegetation communities utilised by the vlei herd included forage species eaten by sable (Appendix III), with the exception of *Aristida junciformis – Arundinella nepaliensis* tall closed grassland, a marshy area with semi-submerged vegetation, where the dominant grass species is *Aristida junciformis,* an unpalatable grass with no grazing value (Van Oudtshoorn 2009).

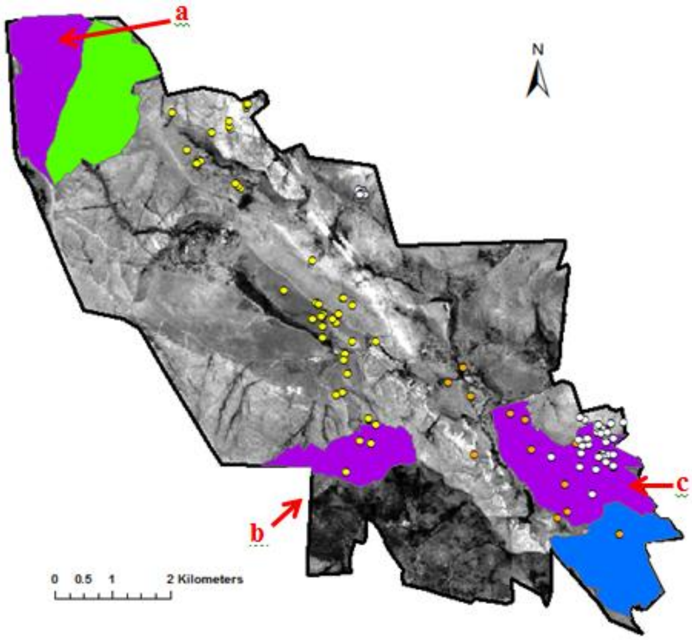
The woodland herd regularly used the *Heteropogon contortus* - *Trachypogon spicatus* tall open woodland vegetation community (Appendix III). This community is divided into a number of sub-communities, the most commonly used being *Tristachya leucotrix* - *Setaria sphacelata* tall sparse woodland. All the vegetation communities used by the woodland herd contained grass species that are eaten by sable (Appendix III). The vegetation communities that were avoided by the woodland herd were mainly in closed woodland areas (Appendix III), and in fact both the woodland and vlei herd used mainly open areas.

The most frequently used vegetation community by the eland herd on the days corresponding to the Landsat images in the dry season was *Heteropogon contortus* - *Faurea saligna* tall open woodland (Appendix III). As eland are mixed feeders; the trees, shrubs, and forbs of each community were also considered. Forbs and grasses in these communities are reported as eaten by eland (Appendix III). Apart from the *Heteropogon contortus* - *Faurea saligna* vegetation community, eland appeared to travel through the landscape without preference for one community or another. Overall, more wooded communities were visited by eland and of the 18 recorded locations, 15 were within wooded areas. Four locations were situated outside the vegetation shapefile and so could not be identified.

GPS locations and burnt areas

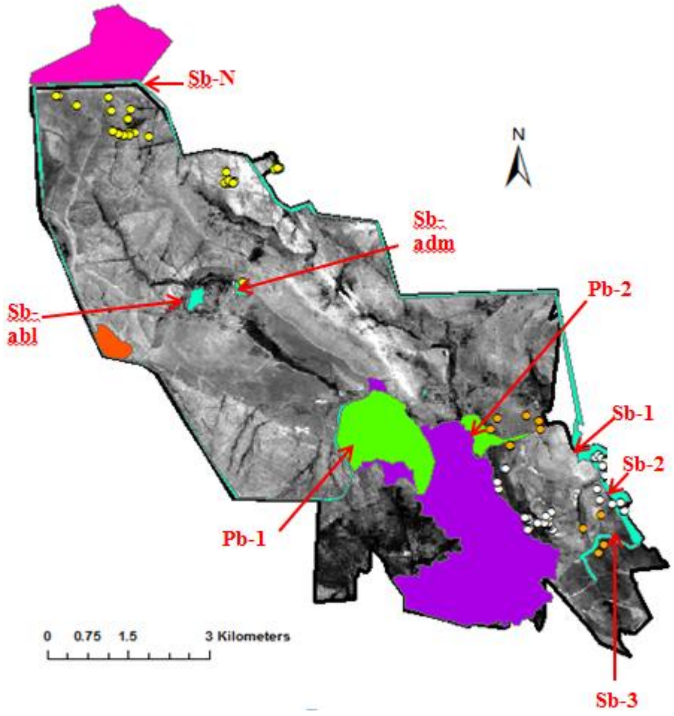
In 2013 only four GPS locations for the vlei herd, coinciding with satellite image 3013196 (17/7/2013), were within a burn (prescribed burn b) set on 1/7/2013 on the SE edge of the plateau (Figure 2.2 a). The vegetation communities that occur within this burnt area and that were used by sable are *Asparagus krebsianus* - *Senecio venosus* high open shrub land, *Heteropogon contortus* - *Faurea saligna* tall open woodland and *Ceterach cordatum* - *Tristachya leucotrix* tall sparse shrub land (Table 2.1).

During the dry season of 2014, very little of the vlei herd's home range was burnt (Figure 2.2 bottom), and none of the locations coinciding with the Landsat images fell within burnt areas. The majority of the forage locations for the woodland herd in the dry season of 2013 were spent within the burned areas (prescribed fire c), set on 1/7/2013 in the southwestern part of the low-lying valleys (Figure 2.2 top). There was only one satellite image (no. 2013196 recorded on 15/7/2013) where the woodland herd was not using the prescribed burnt area. The vegetation communities used by this herd in the burn were *Heteropogon contortus* - *Trachypogon spicatus* tall open woodland and *Trachypogon spicatus* - *Bulbostylis burchellii* short sparse woodland (Table 2.1).



Key	
Forage locations	**Herd**
🟡	Sable vlei
⚪	Sable wood
🟠	Eland

Key	Fire type	Start date
a	Prescribed	1/7/2013
b	Prescribed	1/7/2013
c	Prescribed	1/7/2013
🟩	Runaway	31/7/2013
🟦	Accidental	22/8/2013



Key	Fire type	Start date
	Prescribed burns (Pb)	
Pb-1	Sports field	22/7/2014
Pb-2	Block 9	4/8/2014
	Security burns (Sb)	
Sb-N	Fire break N border	9/6/2014
Sb-1	Fire break 1	1/7/2014
Sb-2	Fire break 2	2/7/2014
Sb-3	Fire break 3	3/7/2014
Sb-adm	Block 4 Admin	8/7/2014
Sb-abl	Block 4 Ablutions	16/7/2014
	Other burns(Ob)	
🟪	Runaway	4/8/2014
🟥	Lightning	22/10/2014
🟪	Wildfire	23/6/2014

Figure 2.2 2013 (top) and 2014 (bottom) burn areas in Kgaswane Mountain Reserve and locations for sable vlei herd, sable woodland herd and eland herd on days coinciding with Landsat images during the dry seasons

Table 2.1 2013-2014 burnt areas in Kgaswane Mountain Reserve, vegetation communities falling within them and the herd that made use of them.

Burn	**Date of burn**	**Vegetation communities**	**Herd**	**No. of locations**
Prescribed a	1/7/2013	*Asparagus krebsianus-Senecio venosus* high open shrubland	Vlei	1
		Heteropogon contortus-Faurea saligna tall open woodland		2
		Ceterach cordatum-Tristachya leucotrix tall sparse shrubland		1
		Lopholaena coriifolia-Lapeirosia sandersonii short open grassland		-
Prescribed b	1/7/2013	*Burkea Africana-Setaria sphacelata* tall open woodland	Woodland	-
		Heteropogon contortus-Trachypogon spicatus tall open woodland		15
		Loudetia flavida-Tristachys bisetaria tall closed shrubland		-
		Trachypogon spicatus-Bulbostylis burchellii short sparse woodland		14
		Trachypogon spicatus-Sphenostylis augustifolia tall closed grassland		-
Prescribed c	1/7/2013	*Senecio venosus-Heteropogon contortus* tall closed woodland	Eland	-
		Lopholaena coriifolia-Lapeirosia sandersonii short open grassland		-
		Olea europaea-Grewia occidentalis tall closed woodland		-
		Aristida transvaalensis-Bulbostylis burchellii tall sparse shrubland		-
		Heteropogon contortus-Faurea saligna tall open woodland		3
		Pteridium aquilinum-Miscanthus junceus tall closed grassland		1
		Trachypogon spicatus-Bulbostylis burchellii short sparse woodland		1
Accidental	22/8/2013	Location inside accidental burn outside vegetation shape-file	Eland	1
Fire break 2	2/7/2014	*Aristida transvaalensis-Bulbostylis burchellii* tall sparse shrubland	Woodland	-
		Asparagus virgata-Celtis africana tall closed woodland		-
		Heteropogon contortus-Faurea saligna tall open woodland		-
		Heteropogon contortus-Trachypogon spicatus tall open woodland		3
		Setaria sphacelata-Themeda triandra tall closed woodland		-
		Senecio venosus-Heteropogon contortus tall closed woodland		-
		Trachypogon spicatus-Bulbostylis burchellii short sparse woodland		-

Contrary to 2013, in 2014 the woodland herd made very little use of the burns. The security burns in this area were limited to the boundary firebreaks on the 1/7/2014, 2/7/2014 and 3/7/2014. The area around some buildings and the sports ground was burnt on 22/7/2014 and a runaway fire was started on 4/8/2014 (Figure 2.2 bottom). When the burn shapefile for 2014 is superimposed on the woodland herd's locations, it appears as if the security burns on the south eastern boundary were heavily utilised, but in fact, although these areas were indeed used by the herd, they were used on 31/5/2014 and 16/6/2014, one and two months before the burns respectively. The only satellite image which recorded locations within the burn was image no. 2014199 (18/7/2014), two weeks after the burn (2/7/2014). Only *Heteropogon contortus* - *Trachypogon spicatus* tall open woodland could be identified as being used in the burn because all the other location points lay outside the vegetation shapefile (Table 2.1).

The fires occurring within the eland herd's home range during the winter of 2013, consisted of a prescribed fire set on 1/7/2013 in the southeastern section of the low-lying areas, and an accidental fire on 22/8/2013, just south of the prescribed burn (Figure 2.2 top). Of the 12 locations for the eland herd falling on the days that coincided with the Landsat images, five were outside of burnt areas, six were located inside the prescribed burn, and one was located inside the accidental burn (Table 2.1). The vegetation communities used by the eland within the burn were *Heteropogon contortus* - *Faurea saligna* tall open woodland, *Pteridium aquilinum* - *Miscanthus junceus* tall closed grassland and *Trachypogon spicatus* - *Bulbostylis burchellii* short sparse woodland (Table 2.1). Of the 11 locations for the eland herd during the dry season of 2014, they were not once found in the burnt areas (Figure 2.2 bottom).

GPS locations and geological substrate

The plateau on which the vlei herd is located is mainly situated on the Magaliesberg Quartzite of the Transvaal Sequence (Table 2.2). In some areas such as isolated patches in the northeastern part of the reserve, the Magaliesberg Quartzite is mixed with Kolobeng Norite, and some of the sable locations occurred there as well (Table 2.2). Of the main vegetation types used by the vlei herd, *Burkea africana* - *Setaria sphacelata* tall open woodland and *Lopholaena coriifolia* - *Lapeirousia sandersonii* short open grassland occur on the Magaliesberg Quartzite of the Transvaal Sequence; and the *Croton grastissimus* - *Combretum molle* short open woodland occurs on a mixture of quartzite and norite of the Bushveld Igneous Complex (Table 2.2).

The geology underlying the range of the woodland herd consists of a mixture of areas of Magaliesberg Quartzite of the Transvaal Sequence, and Kolobeng Norite, an iron-rich rock of the Bushveld Igneous Complex. The majority of the vegetation communities utilised by the woodland herd, occur over Kolobeng Norite of the Bushveld Igneous Complex (Table 2.3). *Heteropogon contortus* - *Faurea saligna* tall open woodland overlies the mix of quartz and norite of the Bushveld Igneous Complex, and *Aristida transvaalensis* - *Bulbostylis burchellii* tall sparse shrubland, *Burkea africana* - *Setaria sphacelata* tall open woodland and *Trachypogon spicatus* - *Sphenostylis augustifolia* tall closed grassland grow on the Magaliesberg Quartzite of the Transvaal Sequence (Table 2.3).

The eland herd is found mainly on vegetation underlain by the Kolobeng Norite rocks of the Bushveld Igneous Complex, although occasionally the vegetation on which they are located overlies Magaliesberg Quartzite of the Transvaal Sequence (Table 2.4). There were only two vegetation units that overlay Magaliesberg Quartzite of the Transvaal Sequence; *Euclea crispa* - *Panicum maximum* tall closed woodland and *Lopholaena coriifolia* - *Lapeirousia sandersonii* short open grassland. All the other vegetation communities grew on the Kolobeng Norite of the Bushveld Igneous Complex, excepting *Pteridium aquilinum* - *Miscanthus junceus* tall closed grassland, which occurs over the quartzite-norite mixture of the Bushveld Igneous Complex (Table 2.4).

Table 2.2 Soil form and geological structure beneath vegetation communities used by the sable vlei herd.

Used vegetation classes	**Soil type**	**Geology**	**No. of locations**
Burkea africana- Setaria sphacelata tall open woodland	Mispah (coarse sand-loam-sand-clay-loam)	Magaliesberg Quartzite-Transvaal Sequence	19
Croton grastissimus- Combretum molle short open woodland	Mispah form (Low clay <10%)	norite & quartzite mix-Bushveld Igneous Complex	13
Lopholaena coriifolia- Lapeirousia sandersonii short open grassland	Mispah form (shallow sand-loam)	Magaliesberg Quartzite-Transvaal Sequence	10
Trachypogon spicatus- Sphenostylis augustifolia tall closed grassland	Glenrosa form (shallow, coarse)	Magaliesberg Quartzite-Transvaal Sequence	7
Indigofera comosa- Schizachyrium sanguineum tall closed grassland	Glenrosa (shallow loam-sand < 0.6m)	Magaliesberg Quartzite-Transvaal Sequence	6
Ruellia patula- Melinus nerviglumis short open woodland	Oakleaf form (alluvial deposits in E valleys)	Kolobeng Norite- Bushveld Igneous Complex	6
Ceterach cordatum- Tristachya leucotrix tall sparse shrubland	Mispah form (Low clay <15%)	Magaliesberg Quartzite-Transvaal Sequence	5
Protea gaguedi- Monocymbium ceresiiforme short open shrubland	Hutton form (deep sand-loam- sand-clay-loam)	Magaliesberg Quartzite-Transvaal Sequence	5
Heteropogon contortus- Faurea saligna tall open woodland	Glenrosa form (Shallow soil)	norite & quartzite mix- Bushveld Igneous Complex	3
Aristida junciforms- Arundinella tall closed grassland	Glenrosa form (sand-sand-loam >1m)	Magaliesberg Quartzite-Transvaal Sequence	2
Aloe greatheadii- Themeda triandra tall open woodland	Hutton form (fine-grained sand-loam)	Kolobeng Norite- Bushveld Igneous Complex	1
Asparagus krebsianus- Senecio venosus high open shrubland	Mispah form (quartz gravel)	Magaliesberg Quartzite-Transvaal Sequence	1
Blumea alata- Parinari capensis tall closed woodland	Glenrosa form (shallow, coarse sand-clay-loam)	norite & quartzite mix- Bushveld Igneous Complex	1
Indigofera burkeana- Rhynchosia totta short closed woodland	Glenrosa (coarse sand-loam-sand-clay-loam)	Magaliesberg Quartzite-Transvaal Sequence	1
Pteridium aquilinum- Miscanthus junceus tall closed grassland	Willowbrook & Kroonstad forms	Magaliesberg Quartzite-Transvaal Sequence	1

Table 2.3 Soil form and geological structure beneath vegetation communities used by the sable woodland herd.

Used vegetation classes	**Soil type**	**Geology**	**No. of locations**
Heteropogon contortus- Trachypogon spicatus tall open woodland	Glenrosa (shallow, coarse-grained soil)	Kolobeng Norite- Bushveld Igneous Complex	28
Trachypogon spicatus- Bulbostylis burchellii short sparse woodland	Glenrosa form (shallow, coarse-grained soils)	Kolobeng Norite- Bushveld Igneous Complex	25
Heteropogon contortus- Faurea saligna tall open woodland	Glenrosa form (shallow soil)	norite & quartzite mix- Bushveld Igneous Complex	9
Asparagus virgata- Celtis africana tall closed woodland	Glenrosa form (moderately deep, fine clay soils)	Kolobeng Norite- Bushveld Igneous Complex	8
Burkea africana- Setaria sphacelata tall open woodland	Mispah (coarse sand-loam to sand-clay-loam)	Magaliesberg Quartzite- Transvaal Sequence	3
Loudetia flavida- Tristachys biseriata tall closed shrubland	Mispah form (sand to sand-clay-loam)	Magaliesberg Quartzite - Transvaal Sequence	3
Senecio venosus- Heteropogon contortus tall closed woodland	Glenrosa (moderately deep, fine clay soils)	Kolobeng Norite- Bushveld Igneous Complex	2
Trachypogon spicatus- Sphenostylis augustifolia tall closed grassland	Glenrosa form (shallow, coarse-grained soils)	Magaliesberg Quartzite - Transvaal Sequence	2
Aristida transvaalensis- Bulbostylis burchellii tall sparse shrubland	Mispah (crests) & Glenrosa (downslope)	Magaliesberg Quartzite - Transvaal Sequence	1

Table 2.4 Soil form and geological structure beneath vegetation communities used by the eland herd.

Used vegetation classes	**Soil type**	**Geology**	**No. of locations**
Heteropogon contortus- Faurea saligna tall open woodland	Glenrosa form (shallow soils)	norite & quartzite mix- Bushveld Igneous Complex	6
Pteridium aquilinum- Miscanthus junceus tall closed grassland	Hutton form (deep, coarse-grained, sandy soil)	norite & quartzite mix- Bushveld Igneous Complex	2
Ruellia cordata- Senecio venosus tall sparse woodland	Hutton form (sand-loam)	Kolobeng Norite- Bushveld Igneous Complex	2
Heteropogon contortus- Trachypogon spicatus tall open woodland	Glenrosa (shallow, coarse)	Kolobeng Norite - Bushveld Igneous Complex	1
Lopholaena coriifolia- Lapeirousia sandersonii short open grassland	Mispah form (shallow sand-loam)	Magaliesberg Quartzite - Transvaal Sequence	1
Olea europaea- Grewia occidentalis tall closed woodland	Hutton form (fine-grained sand-loam to sand-clay)	Kolobeng Norite - Bushveld Igneous Complex	1
Senecio venosus- Heteropogon contortus tall closed woodland	Glenrosa (moderately deep, fine clay soils)	Kolobeng Norite - Bushveld Igneous Complex	1
Setaria sphacelata- Themeda trianda tall closed woodland	Glenrosa & Hutton mix (fine-grained soil)	Kolobeng Norite - Bushveld Igneous Complex	1
Tagetes minuta- Commelina africana Sparse open woodland	Hutton form (loam-sand to sand-loam)	Kolobeng Norite - Bushveld Igneous Complex	1
Trachypogon spicatus- Bulbostylis burchellii short sparse woodland	Glenrosa form (shallow, coarse-grained soil)	Kolobeng Norite - Bushveld Igneous Complex	1

GPS locations and soil forms

The soils underlying the vlei herd locations are mainly of the Mispah Form (Table 2.2), which lies beneath the areas where the *Lopholaena coriifolia - Lapeirousia sandersonii* and *Croton gratissimus - Combretum molle* communities grow. The next most common soils underlying vegetation communities used by the sable herd are from the Glenrosa Form; situated on slopes, on the edges of the central basin and on the summits of the hills in the northeastern part of the reserve. Other soil forms were Hutton, Oakleaf, Willowbrook and Kroonstad forms (Table 2.2), found in and around the central vlei, but the vlei herd was seldomly located in this area. The soil form found in the lowlands where the woodland herd is located, is mainly the Glenrosa form (Table 2.3). Also present, is the Mispah soil form but it is found only in isolated areas with rocks and boulders or on mountain crests and ravine slopes.

Two soil forms predominantly lie beneath the locations of the eland herd (Table 2.4). The first soil form is the Glenrosa Form, which consists of shallow course soils underlain by Kolobeng Norite. This soil form is found on foothill and slopes of southeastern valleys. It underlies the Heteropogon *contortus* - *Trachypogon spicatus* vegetation community. Also present is the Hutton Form, forming the soil template for a number of vegetation communities used by the eland herd (Table 2.4).

Discussion

In KMR there are two sable herds, utilising separate areas of the reserve. The sable vlei herd is situated on the grassland plateau on the summit of the mountains, which includes a vlei. The sable woodland herd is found on the woody slopes and low-lying valleys at the base of the mountains. The woodland herd was found mainly in the southeastern portion of their available range. In KMR the eland's home range encompasses the entire reserve. During the dry season of this study the individual female with the radio collar became part of a smaller herd which stayed in the woody lowlands throughout the study period. The area utilised by the eland was in a similar region to that used by the woodland sable herd.

The sable vlei herd had a total of 32 vegetation communities available to them within their home range, and of these they used 15 on the days corresponding to the Landsat images. The vlei herd was recorded mostly in three vegetation communities characterised by open grassland with sparse trees, in accordance with the expectations of this study and validated by other studies that reported sable preferring open woodland and savanna habitats (Jarman 1972; Wilson and Hirst 1977; Parrini 2006; Owen-Smith *et al.* 2011). These were *Burkea africana* - *Setaria sphacelata* tall open woodland and *Lopholaena coriifolia* - *Lapeirousia sandersonii* short open grassland, overlying Magaliesberg Quartzite of the Transvaal Sequence, and *Croton gratissimus*- *Combretum molle* short open woodland overlying a mixture of quartzite and norite of the Bushveld Igneous Complex (Nel 2000; Norman and Whitfield 2006). All three vegetation communities grow in shallow, coarse sand-loam to sand-clay-loam Mispah soils (Nel 2000).

Other commonly used vegetation communities were *Trachypogon spicatus* - *Sphenostylis augustifolia*, which grows on shallow, coarse Glenrosa soil of the Magaliesberg Quartzite; and *Protea gaguedi* - *Monocymbium ceresiiforme,* occuring in deeper Hutton soils, which have a higher sand content on the quartzite of the plateau (Nel 2000).

Both *Burkea africana* - *Setaria sphacelata* and *Croton gratissimus* - *Combretum molle* had a predominance of trees. Trees have deeper roots than grasses and are able to act as nutrient pumps, making the nutrients more available to shallow grass roots growing within the area of the canopy (Scholes 1990). Prominent grass species eaten by sable, found within these vegetation communities, are *Setaria sphacelata, Trachypogon spicatus, Schizachyrium sanguineum, Diheteropogon amplectens, Themeda triandra* and *Cymbopogon validus* (Parrini 2006).

On 1/7/2013 a burn was initiated in the home range of the vlei herd on the northeastern boarder of the reserve as well as on the southeastern edge of the plateau. Two weeks after the fire, on 15/7/2013, the sable vlei herd utilised the green flush in the *Asparagus krebsianus* - *Senecio venosus* high open shrub land, *Heteropogon contortus* - *Faurea saligna* tall open woodland and *Ceterach cordatum* -*Tristachya leucotrix* tall sparse shrub land in the southeastern burn. Acceptable grasses, which are usually eaten on burnt areas and are found in these communities, are *T. triandra* and *D. amplectens* (Parrini 2006). However, few locations were found in the green flush, which contradict the expectation that sable antelope would utilse the burns. During 2014 the vlei herd made partial use of the previous year's burn, mainly in *Lopholaena coriifolia* - *Lapeirousia sandersonii*, but also in *Trachypogon spicatus* - *Sphenostylis augustifolia* tall closed grassland, *Aloe greatheadii* - *Themeda triandra* tall open woodland and *Protea gaguedi* - *Monocymbium ceresiiforme* open shrubland. This confirms the observations of Parrini and Owen-Smith (2010), in which sable use the previous year's burn as forage productivity and quality was higher in these areas compared to unburned areas.

The sable woodland herd only used ten out of the 28 vegetation communities available to them. The herd foraged most frequently in the *Heteropogon contortus* -*Trachypogon spicatus* tall open woodland vegetation community and *Trachypogon spicatus* - *Bulbostylis burchellii* short sparse woodland. The low-lying woodland area where the sable woodland and the eland herd were situated is largely underlain by the Bushveld Igneous Complex (Nel 2000). Locations were recorded on the iron-rich Kolobeng Norite of the Bushveld Igneous Complex and on a mixture of norite and quartzite, also of the Bushveld Igneous Complex, or on Magaliesberg Quartzite of the Transvaal Sequence.

Both *Heteropogon contortus* - *Trachypogon spicatus* and *Trachypogon spicatus* - *Bulbostylis burchellii* occur on shallow, coarse-grained Glenrosa soils overlying Kolobeng Norite of the Bushveld Igneous Complex (Nel 2000). The grass species found in these communities, which are accepted as forage, all grow in shallow, gravelly, stony soils characteristic of Glenrosa and Mispah soil forms (Nel 2000). These grass species are *Heteropogon contortus, T. spicatus, Tristachya leucotrix, T. trianda, D. amplectans* and *Brachiaria serrata* (Parrini 2006). These two vegetation communities were also among the open woodland areas used by the woodland herd. As the soil in both these areas is shallow and lacking in clay, it cannot be assumed that any green vegetation found there is necessarily due to soil moisture, but rather due to a post-burn flush and in fact, as expected, the woodland herd was making extensive use of these burnt areas, beginning one month after the burn was started until October 2013. This could be explained by the fact that between the prescribed burn and the accidental fire, a large part of the woodland herd's home range was burnt that year. The following year these two vegetation communities were once again continually used, confirming the observation by Parrini and Owen-Smith (2010) that the previous year's burn will be exploited rather than unburned areas. The continued used of the burnt areas could also be the consequence of the extensive area that had been burnt the year before.

Other open vegetation communities in the areas available to the woodland herd that were not utilised contained only one or two suitable grass species and the more heavily wooded vegetation communities were also avoided, even though appropriate forage species were found within them. The only exceptions were *Asparagus virgata* - *Celtis africana* tall closed woodland, *Senecio venosus* - *Heteropogon contortus* tall closed woodland and *Setaria sphacelata* - *Themeda trianda* tall closed woodland, with the common denominator of the highly palatable grass *Panicum maximum*, often found under tree canopies (Treydte *et al*. 2007). Nitrogen fixing leguminous woody plants increases the nutrient content in grasses that grow beneath them (Danso *et al.* 1992; Power *et al.* 2003) and Treydte *et al*. (2007) found that even non-nitrogen fixing trees improved the quality of grasses growing underneath their canopies, especially in drier regions. So during the dry season, grasses such as *P. maximum* growing beneath trees, can become an important source of high quality forage for herbivores (Parrini 2006; Van Der Merwe and Marshal 2012).

For the period of this study the eland herd moved through many different vegetation communities with a similar number of locations found in each community, where many of their preferred browse species occurred. The majority of the locations were within closed, wooded vegetation classes and only three were in open grasslands. It is expected since at this time of the year eland would be mainly browsing as tree leaves retain higher nutrient quality for a longer period than grass (Field 1975). Two locations were found in *Pteridium aquilinum - Miscanthus junceus* tall closed grassland, moist grassland overlying deep clay soils in wetlands, along streams and in drainage lines (Nel 2000). This community was recorded as being utilised about six weeks after the area was burned in 2014, during a period when eland were indeed observed to make extensive use of burned areas (D’Ammando unpublished data).

The area through which the eland browsed is mainly underlain by a mixture of Kolobeng Norite of the Bushveld Igneous Complex and Magaliesberg quartzite of the Transvaal Sequence, commonly found in the Rustenburg Layered Suite of the Bushveld Igneous Complex (Norman and Whitfield 2006). Mainly, the recorded locations occurred on this substrate, or on Kolobeng Norite of the Bushveld Igneous Complex. A few of the locations were underlain by Magaliesberg Quartzite of the Transvaal Sequence. The geological template was similar to the woodland herd, but whereas the woodland herd was found mainly in areas with Glenrosa and Mispah soil forms, the more woody habitats preferred by eland occurred more commonly on Glenrosa and Hutton soil forms. There are five different series of Hutton soils within the reserve (Nel 2000). The differentiation of each series depends on the clay content within the B Horizon, and the amount of leaching that therefore can occur (MacVicar *et al.* 1977). Hutton soils with the highest percentage of sand are found in higher areas of the grassland plateau and summits and are underlain by quartzite. The soils with the highest clay content are found in the low-lying woodland areas that are underlain by norite (Nel 2000). In the lowlands of the reserve, the clay content will be greater and more able to support vegetation such as trees, shrubs and forbs (Ololade 2012).

Contrary to my initial expectation, eland did make use of the burnt areas. The vegetation community that was more frequently used than the others on burnt areas was *Heteropogon contortus* - *Faurea saligna* tall open woodland. This vegetation community and most of the others found within the burnt areas; had few trees and shrubs, containing only forbs and grasses and therefore were not expected to be used by eland in the dry season. In this vegetation community, only isolated stands of *Faurea saligna* trees occurred; a deciduous tree with leaves turning red in autumn (Palgrave 1977). The use of burnt areas is in accordance with the study conducted by D'Ammando *et al.* (2014), who observed eland grazing in burnt areas during this period. Wallington *et al.* (2007) validated this fact by proposing that eland alternate between browsing and grazing depending on the best forage available in each vegetation community. So it is possible that the eland were making opportunistic use of the post-burn green flushes in these areas.

Conclusion

As expected, both sable herds were mostly found in open woodlands, where the benefit of intermittent clumps of trees act as nutrient pumps (Scholes 1990), reserves of soil moisture (Ludwig *et al*. 2003), and consist of organically-rich soil (Sutton *et al*. 2002). These factors all increase the quality of forage (Jarman 1972). The vlei herd also used open grasslands because much of the plateau has poor, acidic soils with a sandy or stony texture; supporting the grass species of the highveld sourveld (Acocks 1988). Contrary to expectations, the sable vlei herd did not make much use of burnt areas within their home range, but were occasionally found to graze in areas that had been burnt the year before, which they are known to do if the quality of the forage in the old burn remains higher that surrounding unburnt areas (Parrini and Owen-Smith 2010).

The woodland herd was mostly located in open woodlands but did make sporadic use of closed woodlands, where *P. maximum* was found; a nutritious grass growing beneath tree canopies and is used in the dry season as a source of high quality forage (Parrini 2006; Marshal *et al.* 2011). The vegetation communities commonly frequented by the woodland sable herd were underlain with shallow, sandy Glenrosa and Mispah soils, with little clay content (Nel 2000), which is consistent with the expectation that sable antelope utilise areas supporting more grass than trees. As most of the woodland herd's home range was burnt in 2013, there was little option but to graze the green flush. The following year the burns were not used at all. Instead the same vegetation communities were favoured as the previous year, possibly due to the widespread burns in the area leaving few vegetation communities with higher productivity than adjacent areas (Parrini and Owen-Smith 2010).

The eland herd utilised woodlands underlain by deeper Hutton soils consisting of sand, loam and clay (Nel 2000). This soil would be supportive of deeper-rooted tree architecture and able to supply the nutritional and moisture needs of closed vegetation communities (Borchert 1999). This is consistent with the expectation and indeed the fact that eland prefer to browse during the dry season when resources are limited (Hillman 1987). However, diverging from expectation, eland were frequently found in a post-burn green flush, in a vegetation community supported by shallow, sandy Glenrosa soils. This is in agreement with Wallington *et al.* (2007), who states that eland will opportunistically take advantage of the best forage within their reach.

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CHAPTER 3 A COMPARISON OF LANDSAT 8 INDICES TO PREDICT RESOURCE SELECTION BY SABLE ANTELOPE (*HIPPOTRAGUS NIGER*) AND ELAND (*TRAGELAPHUS ORYX*).

Introduction

Satellite indices are calculated from multispectral data collected from electromagnetic bands within the visible, near infrared (NIR), thermal infrared (TIR) or shortwave infrared (SWIR) spectral regions of the electromagnetic field (Dogan 2009). Satellite sensors capture light that hits a target area on the Earth's surface. This light is reflected, transmitted or absorbed; depending on the characteristic of the surface and the wavelength of the light (Jackson and Huete 1991). By means of a series of algorithms, it is possible to use this information to identify various ecological characteristics, which create different spectral signatures that can describe the physical features of the environment at the landscape level (Escadafal and Huete 1992). Vegetation indices are based on the assumption that vegetation absorbs visible red and reflects near infrared (NIR) light (Gillieson *et al*. 2006; Philpot 2011). This depends on the amount of chlorophyll and the surface area of the plant that is exposed to the light. Hence, these indices are often used to measure greenness in vegetation (Pettorelli *et al.* 2005 a). The ability of vegetation indices to quantify greenness benefits the study of animal distribution patterns because it contributes towards understanding various aspects of ecology such as foraging choices, space use within the home range and dispersal behaviour within the landscape (Senft *et al*. 1987). These distribution patterns are influenced by biotic and abiotic factors. For example, at the spatial resolution of the home range, biotic factors such as forage quantity and quality are an important part in the local distribution of animals (Bailey *et al.* 1996; Chirima *et al.* 2013). Abiotic factors, such as geology, topography, climate and distance to water mostly operate on a larger scale (Chirima *et al.* 2013), and are the boundaries within which biotic factors are shaped (Bailey *et al.* 1996).

NDVI (Normalised Difference Vegetation Index) is frequently used vegetation index to demonstrate spatial and temporal distribution of vegetation cover and primary productivity relative to animal distribution (Beck *et al.* 2008; Pettorelli *et al.* 2011). NDVI seems to be associated with animal locations in many, but not all studies. For example, in the Associate Private Nature Reserves adjacent to the Kruger National Park, NDVI values adequately demonstrated that elephant (*Loxodonta africana*) selected for greenness in the wet season (Marshal *et al.* 2011). In Norway, seasonal changes in greenness as measured by NDVI have been linked to migration in red deer (*Cervus elaphus*) (Pettorelli *et al*. 2005 b; Bischof *et al.* 2012). Using NDVI, African buffalo (*Syncerus caffer*) locations in the Kruger National Park have been related to food quantity and quality with regards to the underlying geological substratum (Winnie *et al*. 2008). However, NDVI is not always linked to animal distribution. When testing presence or absence data in the Kalahari in Botswana; Verlinden and Masogo (1997) found that eland (*Tragelaphus oryx*), wildebeest (*Connochaetes taurinus*) and springbok (*Antidorcas marsupialis*), did not show significant associations with greenness or NDVI, whereas gemsbok (*Oryx gazella*), hartebeest (*Alcephalus buselaphus*) and ostrich (*Struthio camelus*) did. These inconsistencies seem to link animal locations with additional environmental factors, or suggest that NDVI might not be a suitable index for greenness in this area. Due to the heterogeneous nature of the environment; simply measuring the presence of green biomass, which is not always related to high NDVI values, may be ambiguous (Verlinden and Masogo 1997).

However, it is important to consider that depending on the spatial resolution of the satellite, there are many factors that affect NDVI values within one pixel. These include plant architecture and height, species composition, vegetation cover, vegetation vigour, topography and altitude (Pettorelli *et al.* 2005 a). Consequently the same NDVI value might represent different conditions in different plant communities (Pettorelli *et al.* 2005 a). In savannas and other heterogeneous environments, the combination of trees and grasses is significant for describing the utilisation of various vegetation communities by different species of herbivores (Scanlon *et al.* 2002). The use of NDVI can be temporally confounded by the fact that as the vegetation becomes greener, the amount of plant matter increases, so it is difficult to evaluate whether NDVI is measuring the greenness (quality) or the biomass (quantity) of vegetation (Winnie *et al.* 2008). In their study in Kruger National Park, Winnie *et al.* (2008) found that

NDVI values for woody cover overlying granite was similar to values for tall green grass covering basaltic structures, which have higher quality forage.

This is further complicated by the fact that certain tree species will initiate budding due to lengthening photoperiod as the summer approaches, whereas others will be induced by soil moisture (Archibald and Scholes 2007); suggesting that the source of greenness values are hard to identify. Trees can store more water and nutrients than grasses, which are dependent on rainfall and so rely on soil moisture to initiate their seasonal rejuvenation (Scanlon *et al*. 2002; Archibald and Scholes 2007). Therefore although satellite imagery records greenness values at the scale of the landscape, it is not able to distinguish between vegetation types at a finer scale (Winnie *et al.* 2008) or predict the difference between onset of growth of browsing and grazing resources (Archibald and Scholes 2007). NDVI should therefore be used in conjunction with knowledge of other biological parameters of the area (Verlinden and Masogo 1997), or satellite imagery with a finer resolution (Archibald and Scholes 2007).

There is a direct relationship between rainfall and NDVI values, but only up to a threshold of approximately 500 mm per year, after which NDVI values level off as greenness saturation is reached (Nicholson and Farrar 1994). This happens at lower thresholds over Botswana than over East Africa or the Sahel, which suggests that rain-use efficiency and therefore biomass productivity is possibly more a function of underlying soil type than NDVI values (Farrar *et al*. 1994). Furthermore, the NDVI values measured over Botswana may be influenced by higher soil reflectivity caused by more calcium carbonate in the soil (Ringrose *et al*. 1989) than in the other two regions. Therefore NDVI values used as a proxy for vegetation productivity and hence animal locations could differ depending on the region being studied, and other local factors, such as in this case, soil reflectivity.

The relationship between NDVI, NDWI (Normalised Difference Water Index) and soil moisture was assessed by Gu *et al*. (2008) to see how these vegetation indices reacted to changes in soil moisture levels. They found that both vegetation indices and soil moisture depended on the type of vegetation cover and the underlying soil type. Their results showed that homogenous vegetation cover (such as grasslands or closed woodlands) with soils containing a higher clay content, were more strongly associated with soil moisture than areas with heterogeneous vegetation cover (savanna or open woodlands) containing soils with higher sand content. Therefore, both spatially and temporally, the efficacy of soil to retain moisture could be regarded as a better indicator of biomass productivity than NDVI (Farrar *et al*. 1994).

Soil reflectivity is an important factor influencing NDVI, primarily in savannas and woodlands where vegetation cover is heterogeneous (Huete *et al.* 1985; Najeeb 2013). This is because different soil types vary in the amount of red light they reflect compared to infrared light and so they have different brightness values. Therefore soil reflectivity either inceases or decreases NDVI values depending on the exposed soil type and irrespective of the vegetation greenness values (Escadafal and Huete 1992). Thus, the measurement of vegetation is dependent on the influence of soil radiation values (Huete and Jackson 1988).

Soil mineral content is another dynamic linking plant growth forms and greenness values to animal distribution because the occurrence of minerals essential for plant growth across the landscape will define vegetation communities and therefore where animals choose to forage (McNaughton 1988; Lillesand *et al.* 2008). The arrangement of minerals in the soil is such that primary minerals occur in the sand and silt fractions; and secondary minerals in the clay fraction (Palm *et al.* 2007). Soil fertility depends on the type of weatherable minerals in sand and silt, and the number of ion exchange sites in clay (Palm *et al.* 2007). For example, iron is a micronutrient essential for photosynthesis as it catalyses chlorophyll production (Dogan 2009). Two indicators of iron are ferrous minerals and iron oxide (Escadafal and Huete 1992). Exploring these factors may lead to deeper understanding of ecological functioning explaining why animal distribution occurs as it does within the landscape.

This study aims to determine whether there are further indicators other than using NDVI alone, to improve the explanation of animal distribution patterns. In order to test this, I used the locations of two sable antelope (*Hippotragus niger*) herds and one eland (*Tragelaphus oryx*) herd in Kgaswane Mountain Reserve (KMR) during the dry season of 2013 and 2014. The two sable herds occupied areas with different characteristics. One of the herds (named the vlei herd) occupied the grassland of a high plateau including a wetland; the other herd (named the woodland herd) was located in the wooded valleys and open woody lowlands. The eland herd was found in the same area as the sable woodland herd. Because the study included grazers (sable antelope) and mixed feeders that browse in the dry season (eland), I was able to evaluate how the results of the satellite indices that best represented the locations of each species, implied discrepancies because of their different diets. Moreover, as the two sable herds were found in different areas, I was able to compare the variations between the two herds related to the use of areas with different characteristics.

The indices considered in this study besides NDVI, were other vegetation indices including SAVI (Soil Adjusted Vegetation Index), which adjusts for the influence of soil radiation (Huete & Jackson 1988), VARIgreen (Visible Atmospherically Resistant Index) and GARI (Green Atmospherically Resistant Index), which compensate for the atmospheric scattering of red light (Holben 1986). NDWI (Normalised Difference Water Index) was used as a proxy for soil moisture (Loyd, *pers. comm.* 2014). NDWI measures the liquid water in leaf molecules, or bioavailable water in vegetation, which is directly affected by soil moisture (Gao 1996). The last set of indices included in this study were mineral composite indices that assess the different spectral signatures of clay minerals, ferrous minerals and iron oxide, calculated from bands within the visible, near infrared and thermal infrared spectral regions (Dogon 2009; Escadafal and Huete 1992).

The objectives of this study are 1) to assess the ability of NDVI, SAVI, VARIgreen, GARI, NDWI and mineral composite indices derived from Landsat 8 to describe herbivore locations within the landscape, and 2) to determine whether similar indices would be consistent for different habitats and different herbivore species, by comparing two sable herds occurring in different areas and one sable and one eland herd occurring in the same area. I expected: 1) NDVI to be the best predictor of used locations for the the sable antelope herd in the open grassland and the eland herd in the closed woodland, but not for the sable antelope herd found in the open woodland; 2) SAVI to improve NDVI in partially vegetated areas, during the dry season when biomass is low; 3) the atmospherically resistant greenness indices VARIgreen and GARI to enhance NDVI values as during winter air pollution typically increases due to veld and domestic fires and inversion layers; 4) NDWI to be a relevant index in areas with soils capable of retaining moisture (i.e. closed woodland).

Methods

Data collection and analysis

I downloaded Landsat 8 images for KMR (25 43ºS, 27 11ºE) for the period 15/7/2013 to 4/9/2014, from Earth Explorer USGS (http://earthexplorer.usgs.gov/) and imported them into ArcGIS 10.2 (Esri ® ArcMap ™) for data analysis. Landsat 8 images are processed at standard terrain correction (Level 1 T) and are orthorectified consistently with all Landsat 1 to 7 level 1 products. This level of correction provides for topographic accuracy by incorporating ground control points while using a Digital Elevation Model (DEM). The images used at the time of this study were not atmospherically corrected although in December 2014, Landsat 8 level 2 A product has been released, which corrects surface reflectance for atmospheric effects using a cloud mask, a cloud shadow mask, a water mask and a snow mask. The pixel size of the images is 30 m for OLI multispectral bands 1 to 7 and band 9; 15 m for OLI panchromatic band 8; and the TIRS bands 10 and 11 are collected at 100 m but resampled to 30 m to match the OLI multispectral bands. The data characteristics are GeoTIFF data format with Cubic Convolution (CC) resampling and North-Up (MAP) orientation. The map projection is Universal Transverse Mercator (UTM) and World Geodetic System (WGS) 84 datum (www.landsat.usgs.gov/landsat8.php). I omitted images with poor visibility due to clouds, and as there were only two images that had clear skies during the wet season, I excluded the wet season and therefore the final images I used all occurred in the dry season (Appendix I). I projected the images to WGS 1984 UTM 36S.

Each Landsat 8 image is comprised of 11 bands of the electromagnetic spectrum, from which I calculated the following indices:

Vegetation indices

1. NDVI (Normalised Difference Vegetation Index) = (NIR - red)/(NIR + red)

   Where NIR = near infrared band 5, red = red band 4. NDVI values range between + 1 and – 1.

2. SAVI (Soil Adjusted Vegetation Index) = (NIR - red)/(NIR+ red +L) x (1 + L)

   Where L is an adjustment factor representing a graphical line (soil line) indicating the soil spectral variation vs. increasing soil brightness (Huete, 1988). L = 0.5 is used as a default value for the calculation because Huete (1988) found the value of L = 0.5 to be optimal to reduce soil noise over the full range of vegetation canopy types. When L = 0, vegetation cover is very high and SAVI approximates NDVI (Najeeb 2013).

3. GARI (Green Atmospherically Resistant Index) = (NIR- [green – (blue – red)])/(NIR + [green – (blue – red)])

   Where NIR= near infrared band 5, green = green band 3, blue = deep blue band 1, red = red band.

4. VARIgreen (Visible Atmospherically Resistant Index) = (green-red)/(green-red-blue)

   Where green = green band 3, red = red band 4, blue = deep blue band 1.

Soil moisture index

1. NDWI (Normalised Difference Water Index) = (NIR-SWIR)/(NIR+SWIR)

Where SWIR= short wave infrared band 6 or 7. Both versions were calculated.

Mineral composite indices

1. Clay minerals = (SWIR 6)/(SWIR 7)

   Where SWIR = shortwave infrared band 6 and band 7.

2. Ferrous minerals = SWIR/NIR

   Where SWIR = short wave infrared band 6 or band 7. NIR = near infrared band 5.

3. Iron oxide = (visible red) / (visible blue)

   Where visible red = red band 4, visible blue = deep blue band 1.

On Landsat 8, deep blue band 1 has been introduced for the first time. It tracks airborne particles of dust and smoke and can be used to alleviate ‘noise’ produced by the scattering of atmospheric aerosols. For the sake of continuity, the normal blue band 2, which was measured in all previous Landsat missions, is also present on Landsat 8. The algorithms for the two atmospherically sensitive greenness indices used in this study; VARIgreen and GARI, could be applied using two alternative blue bands. Other indices that could be calculated using alternative bandwidths were the SWIR (Short Wave Infra-Red) bands 6 or 7 used in the calculation of the ferrous minerals and NDWI indices. I calculated the algorithms using the deep blue band 1 and blue band 2 and then I tested the distribution of the values of band 1 versus band 2 to see whether they overlapped (Figure 3.1 and 3.2). I found that the distributions of data for both indices were similar at both bandwidths, so I discarded band 2 and only used band 1. I then calculated the ferrous minerals and NDWI indices using both SWIR (Short Wave Infra-Red) bands 6 & 7 (Figure 3.3 and 3.4) as sources differ as to the preference of each range (Loyd, *pers comm,* 2014). The distribution of their values did not overlap so I included both versions of the indices.

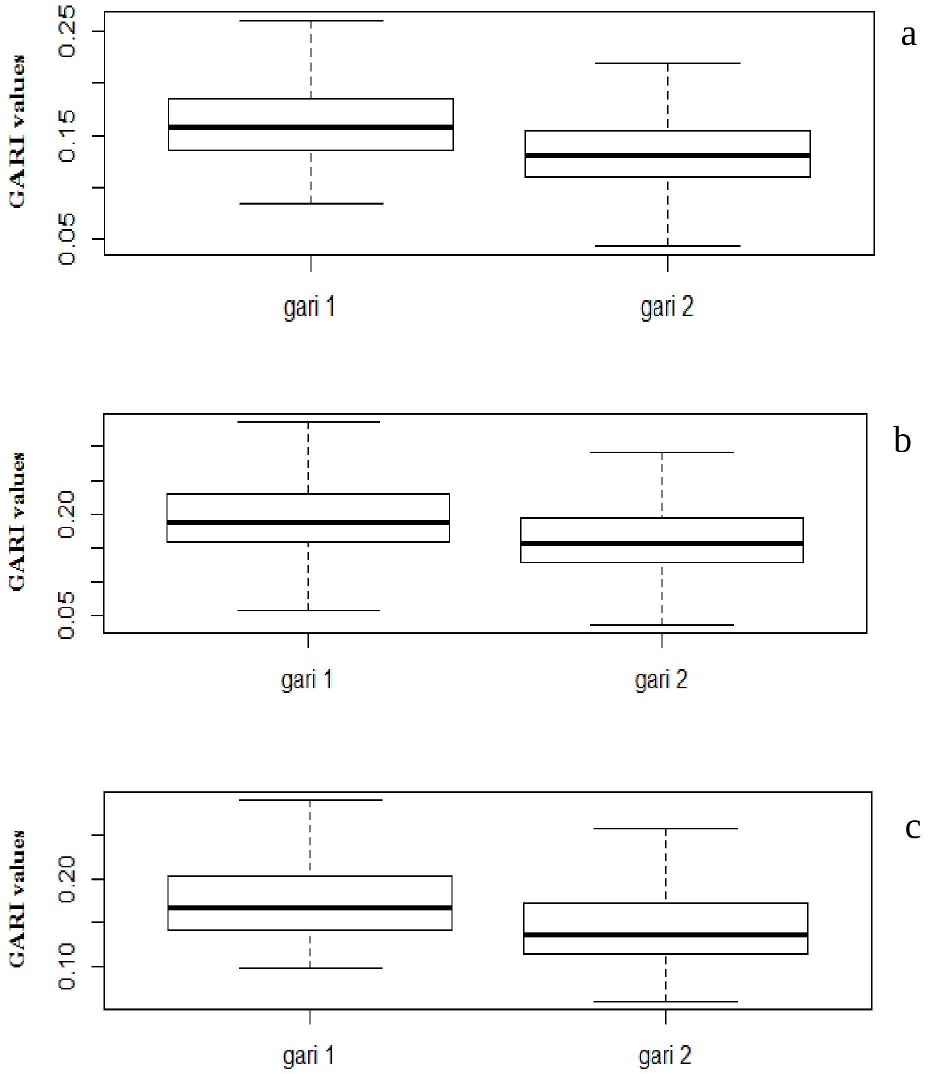

Figure 3.1 Boxplots comparing distribution of GARI 1(calculated using band number 1) and GARI 2 (calculated using band number 2) for: a.) sable antelope vlei herd, b.) sable antelope woodland herd, c.) eland herd.

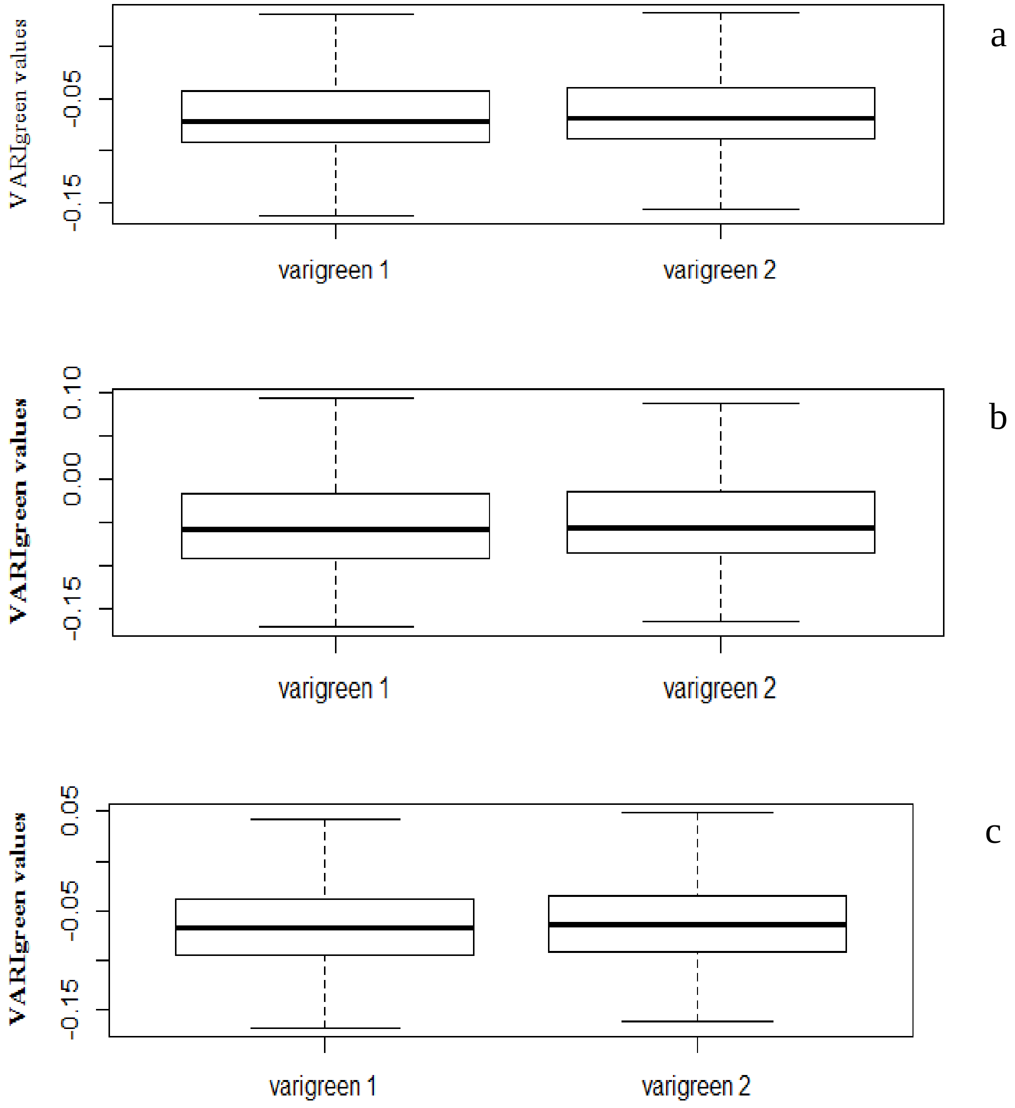

Figure 3.2 Boxplots comparing distribution of VARIgreen1 (calculated using band number 1) and 2 (calculated using band number 2) for: a.) sable antelope vlei herd, b.) sable antelope woodland herd, c.) eland herd.

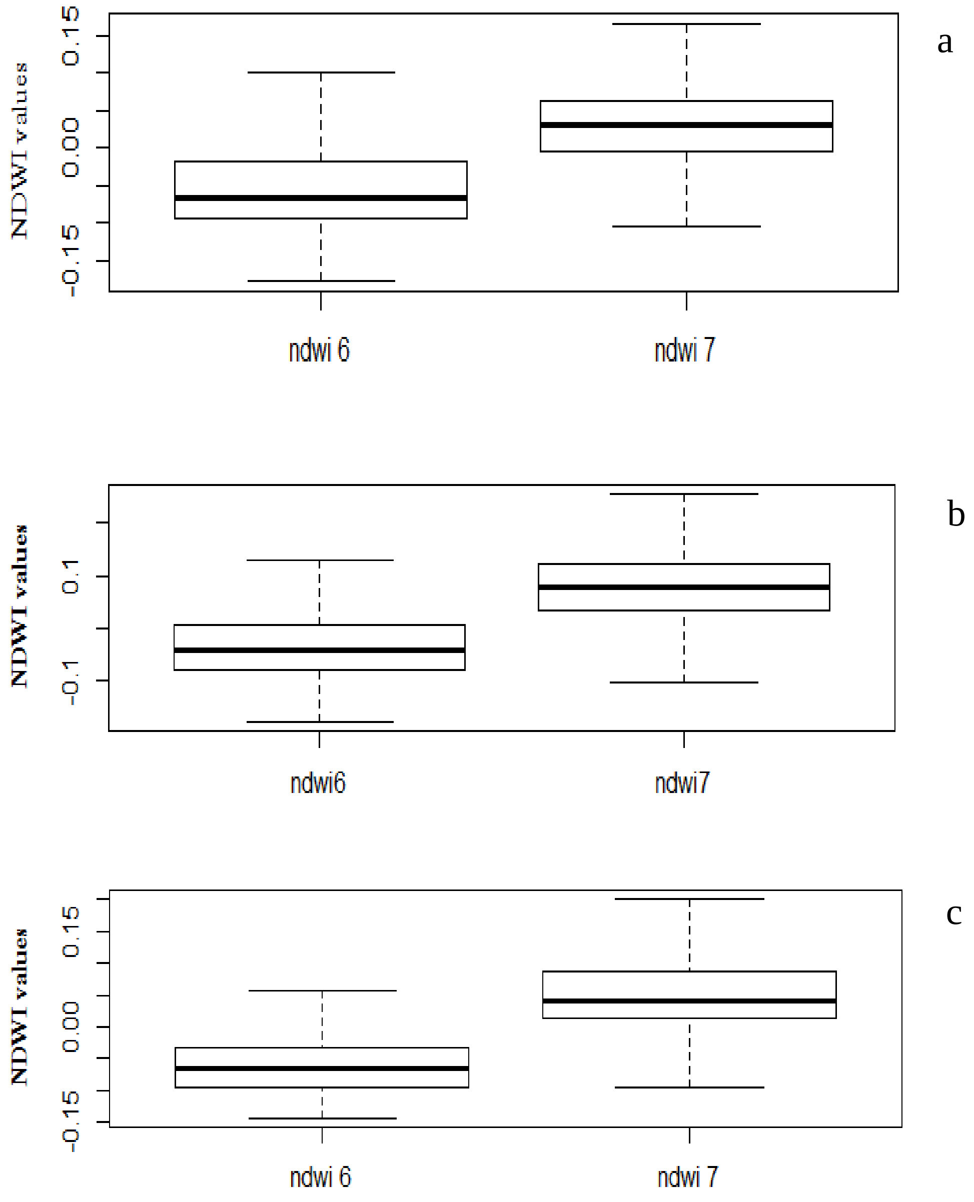

Figure 3.3 Boxplots comparing distribution of NDWI 6 (calculated using band 6) and NDWI 7 (calculated using band 7) for: a.) sable antelope vlei herd, b.) sable antelope woodland herd, c.) eland herd.

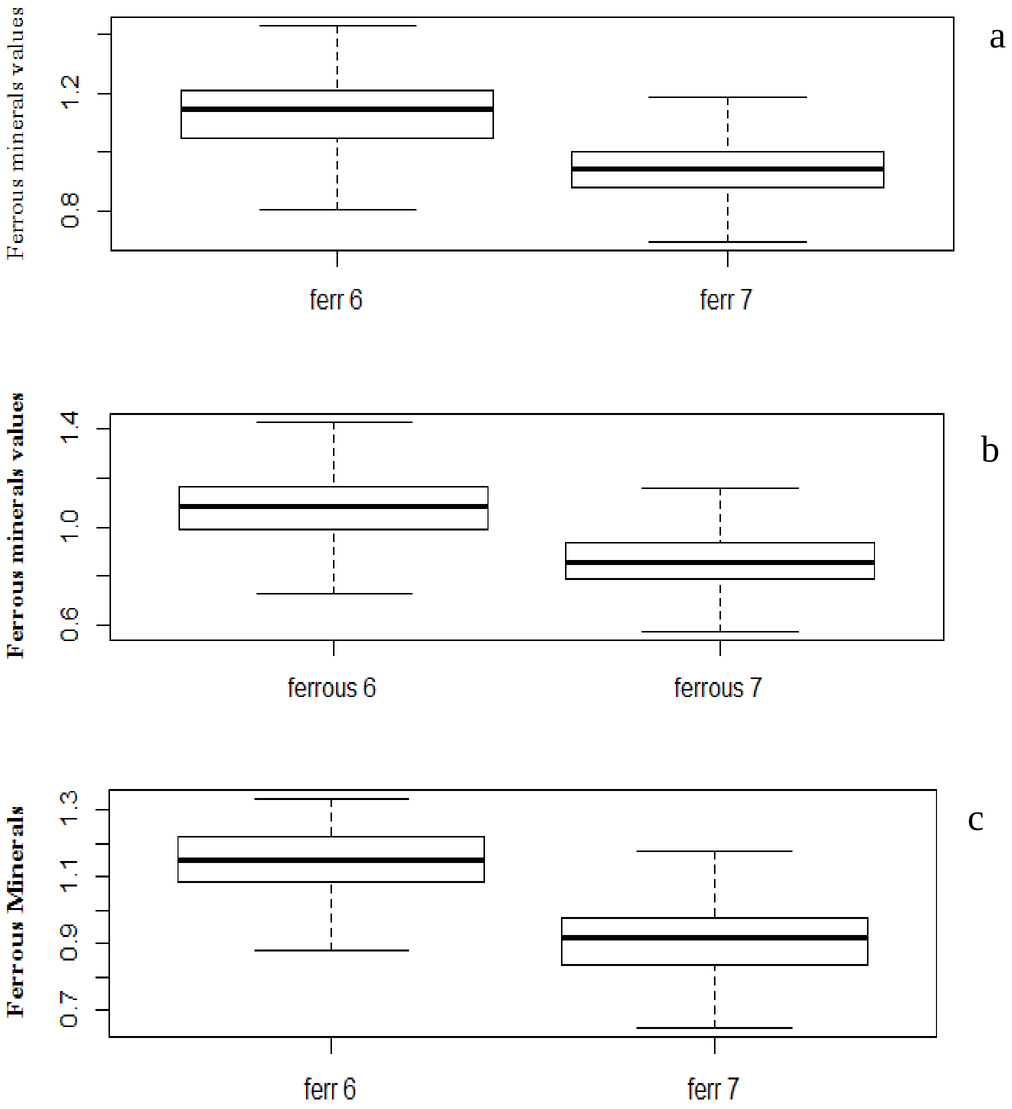

Figure 3.4 Boxplots comparing distribution of ferrous minerals 6 (calculated using band 6) and 7 (calculated using band 7) for: a.) sable antelope vlei herd, b.) sable antelope woodland herd, c.) eland herd.

Two sable antelope females from two different herds and one eland female were collared with satellite GPS collars (see Chapter 2 for details) providing data from 6/1/2012 to 4/8/2014 for sable, and from 17/7/2013 to 4/9/2014 for eland. By means of the spatial analyst tool in ArcGIS 10.2, I created 100% Multiple Convex Polygons (MCPs) of each home range, using all the GPS location data from 2012 to 2014 (see Chapter 2) to determine the areas available to each herd. In all further analysis, I only used the GPS locations matching days for which I had Landsat images (Appendix II). Then for each Landsat image day, I only used morning and evening locations, which were more likely to correspond to animal foraging times. To represent available, but non-used locations, I generated 1:10 random sample locations within the MCPs of each of the herds. In order to arrive at this ratio, I verified that 1:10 was indeed a representative ratio of what was available by comparing each derived index value from all pixels within the entire MCP, to a ratio 1:100 and 1:10 random points. Using the 1:10 ratio for the 12 satellite images, I sampled a total of 89 used vs. 890 available locations for the sable vlei herd; 96 used vs. 960 available for the sable woodland herd; and 23 used vs. 230 available for the eland herd. I therefore defined the word 'available' as the random GPS locations that fall within the 100% MCP. I then extracted the values of the indices at both the used locations and random locations.

In order to investigate whether there was a relationship between used locations and one or more of the various indices tested in this study; I used the *glm* (generalised linear model) function in the Ime4 package to perform a logistic regression analysis in R (R Development Core Team 2013). I used the *glm* function because all the variables were continuous. The explanatory (predictor) variables were the indices and the binary variable being whether a location was used or not used (available).

To avoid having correlated explanatory variables in the same model, for each model I only included indices that were not correlated. I then used the AICc, a version of the Akaike information procedure (AIC), corrected for small samples, to perform model selection among the set of candidate models (Burnham and Anderson 2004). AICc is computed by the following equation:

$\mathrm{AICc} = \mathrm{AIC} + 2\,k\,(k+1) / n - k - 1$ (Symonds and Moussali 2011)

Where k is the number of fitted parameters in the most complex model and n is the sample size (Symonds and Moussali 2011).

The resulting $\mathrm{AIC_c}$ models were then ranked according to the difference between the best ranked $\mathrm{AIC}_{c\,(min)}$ model and each other competing model (i). This statistical outcome is called delta AIC ($\triangle$AIC):

$\triangle AIC_i = AIC_i - AIC_{min}$

In order to normalise the model likelihoods so that they equal one and can then be treated as probabilities (Burnham and & Anderson 2004), I calculated the Akaike weights (w_i) of the models and then ranked the variables with the most accumulative weight, by calculating the sum of the weights of all the models in which a variable was present, to determine the most important variable.

Results

Resource use versus availability for sable antelope and eland in KMR was examined in relation to satellite images derived from Landsat 8. As the logistic regression models for each data set resulted in different indices fitting the best model, I have discussed each herd separately below.

Sable Vlei Herd

For the sable vlei herd most indices were correlated (Table 3.1). Therefore I ran models for each of the indices separately and included four additive models (NDVI + iron, SAVI + iron, NDVI + VARIgreen and SAVI + VARIgreen), illustrating the added effects of the predictor variables (i.e. NDVI, SAVI and iron) on the response variable (location). Two candidate models scored the same lowest AICc value (Table 3.2). These were models 6sv (locations ~NDVI), showing the effect of the predictor variable NDVI on the response variable, the use of location; and model 9sv (locations ~ SAVI) showing the effect of SAVI.

Table 3.1 Sable antelope vlei herd correlation results for Landsat 8 indices. The non-significant correlations are shown in grey

	clay	ferr 6	ferr 7	GARI	iron	NDVI	NDWI 6	NDWI 7	SAVI	VARIgreen
clay		0.0720 (0.023)	-0.407 (2E-07)	0.556 (2E-07)	0.085 (0.008)	0.655 (2E-07)	-0.072 (0.024)	0.407 (2E-07)	0.655 (2E-07)	-0.152 (1.74E-06)
ferr 6			0.841 (2E-07)	-0.472 (2E-07)	0.369 (2E-07)	-0.426 (2E-07)	-1.000 (2E-07)	-0.841 (2E-07)	-0.426 (2E-07)	-0.495 (2E-07)
ferr 7				-0.719 (2E-07)	0.288 (2E-07)	-0.719 (2E-07)	-0.841 (2E-07)	-1.000 (2E-07)	-0.719 (2E-07)	-0.363 (2E-07)
GARI					-0.464 (2E-07)	0.806 (2E-07)	0.472 (2E-07)	0.719 (2E-07)	0.806 (2E-07)	0.419 (2E-07)
iron						0.0203 (0.526)	-0.369 (2E-07)	-0.288 (2E-07)	0.0203 (0.526)	-0.946 (2E-07)
NDVI							0.426 (2E-07)	0.719 (2E-07)	1.000 (2E-07)	0.0213 (0.505)
NDWI 6								0.841 (2E-07)	0.426 (2E-07)	0.495 (2E-07)
NDWI 7									0.719 (2E-07)	0.363 (2E-07)
SAVI										0.0213 (0.505)
VARIgreen										

Top no=correlation coefficient r, bottom no=p value, clay= clay minerals, ferr.6= ferrous minerals using band 6, ferr.7= ferrous minerals using band 7, GARI =.1 Green Atmospherically Resistant index using band 1, iron= iron oxide, NDVI =Near Difference Vegetation Index, NDWI.6= Near Difference Water Index using band 6, NDWI.7= Near Difference water Index using band 7, SAVI =Soil Adjusted Vegetation Index, VARIgreen.1 =Visible Atmospherically Resistant Index using band 1.

Table 3.2 Candidate mixed models and their related statistics, describing forage locations of sable vlei herd in Kgaswane Mountain Reserve, based on satellite indices generated from Landsat 8

Model	Fixed effects	AICc	△AICc	Wi(AICc)	df
6sv	locations~NDVI	609.55	0.00	0.27	1034
9sv	locations~SAVI	609.55	0.00	0.27	1034
13sv	locations~NDVI+VARIgreen1	611.27	1.72	0.11	1034
14sv	locations~SAVI+VARIgreen1	611.27	1.72	0.11	1034
11sv	locations~NDVI+iron	611.55	1.99	0.10	1034
12sv	locations~SAVI+iron	611.55	1.99	0.10	1034
4sv	locations~GARI 1	613.12	3.56	0.04	1034
3sv	locations~ferr 7	620.05	10.50	0.00	1034
8sv	locations~NDWI 7	620.59	11.03	0.00	1034
7sv	locations~NDWI 6	626.12	16.57	0.00	1034
2sv	locations~ferr 6	626.86	17.31	0.00	1034
1sv	locations~clay	631.83	22.27	0.00	1034
10sv	locations~VARIgreen 1	635.77	26.21	0.00	1034
nullmodel	locations~1	636.78	27.22	0.00	1034
5sv	locations~iron	637.18	27.62	0.00	1034

AICc= Akaike's Information Criterion adjusted for smaller samples, △ AIC= change in index value between T_n and T_{n-1},Wi (AICc) = rounded AIC weights, df= degrees of freedom.

These two models together have a 54% probability of being the best models (Table 3.2). Other models that had △ AICc < 2 and were therefore considered, were 13sv (locations ~ NDVI + VARIgreen1), showing the sum of the individual effects of NDVI and the atmospherically sensitive greenness index VARIgreen 1; model 14sv (locations ~ SAVI + VARIgreen1); model 11sv (locations ~ NDVI + iron) and model 12sv (locations ~ SAVI + iron), even though their weights were only 10% each (Table 3.2).

The rank factors showing variables with the most accumulative weights (weight > 0.20) were NDVI (0.48), SAVI (0.48), VARIgreen (0.22) and iron (0.20) (Table 3.3). The sable vlei herd was using locations with higher NDVI , SAVI and VARIgreen values than what was randomly available (Figure 3.5 a, b and c) and with lower iron oxide values compared to the random non-used locations (Figure 3.5 d).

This figure does not illustrate the comparison of models, but is a visual representation of the values of the ‘used’ versus ‘available’ as indicated by the accumulative weight of the important variables.

Table 3.3 Rank factors showing variables with the most accumulative weight for each herd

Variable	Sable vlei herd	Sable woodland herd	Eland herd
Clay minerals	-	0.97	0.14
Ferrous 6	-	-	-
Ferrous 7	-	-	-
Iron	0.20	-	0.49
NDVI	0.48	-	0.17
SAVI	0.48	-	0.17
GARI 1	0.04	0.03	-
VARIgreen 1	0.22	-	0.14
NDWI 6	-	-	0.11
NDWI 7	-	-	-

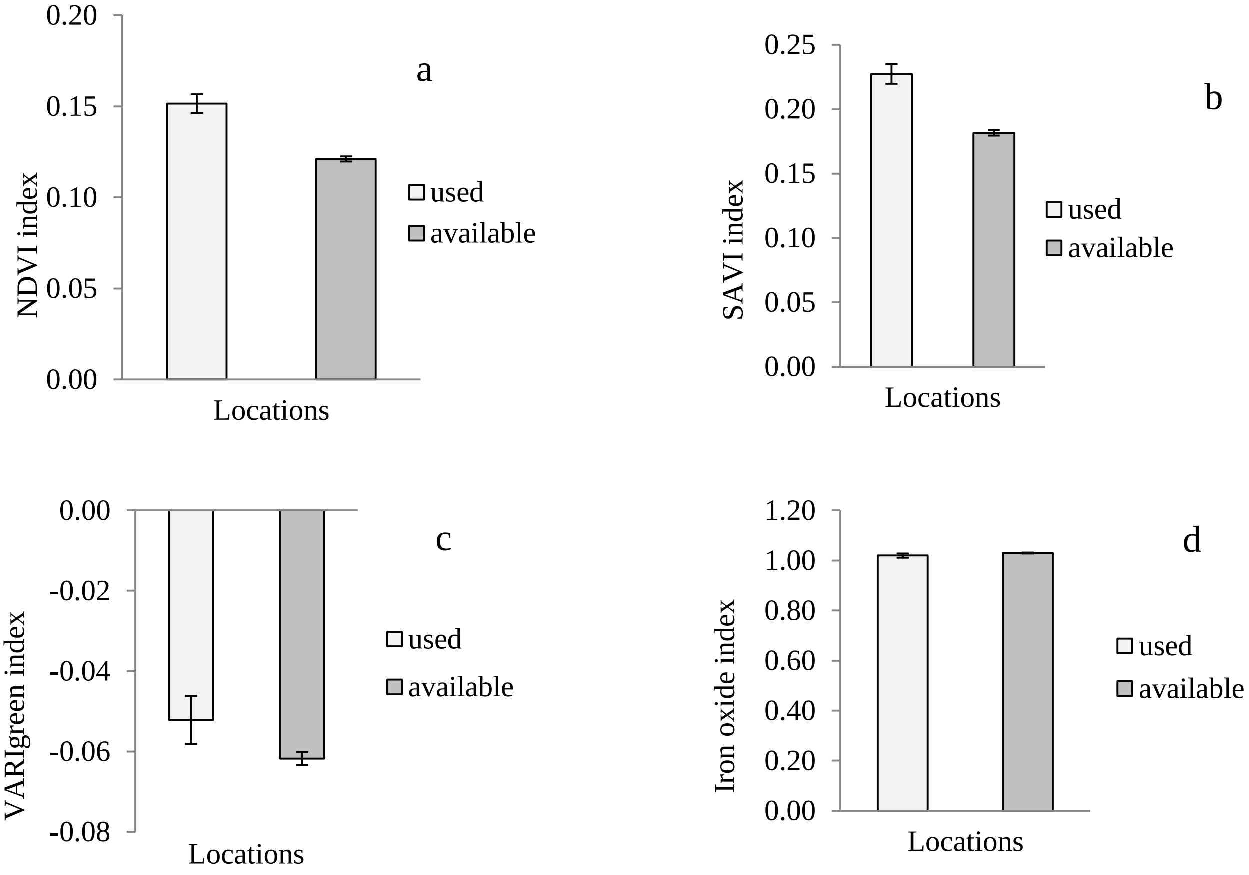

Figure 3.5 Indices values for used versus available locations for sable vlei herd, a) NDVI, b) SAVI, c) VARIgreen and d) iron oxide. The error bars show the standard error.

Sable Woodland Herd

All the variables were correlated for the woodland herd (Table 3.4) and therefore only models with one variable each were built. This means that the rank order of the variables coincided with the rank order of the models. The best model for the sable woodland herd, was model 1sw (locations ~ clay), with a weight of 97%. This model represents the effect of the predictor variable clay minerals on the response variable (Table 3.5).

Table 3.4 Sable woodland herd correlation results for indices. All indices are correlated.

	clay	ferr 6	ferr 7	GARI	iron	NDVI	NDWI 6	NDWI 7	SAVI	VARIgreen
clay		-0.310 (2E-07)	-0.566 (2E-07)	0.540 (2E-07)	0.193 (3.59E-10)	0.722 (2E-07)	0.312 (2E-07)	0.574 (2E-07)	0.722 (2E-07)	-0.128 (3.22E-05)
ferr 6			0.939 (2E-07)	-0.801 (2E-07)	0.464 (2E-07)	-0.696 (2E-07)	-1.000 (2E-07)	-0.934 (2E-07)	-0.696 (2E-07)	-0.576 (2E-07)
ferr 7				-0.875 (2E-07)	0.329 (2E-07)	-0.846 (2E-07)	-0.938 (2E-07)	-0.995 (2E-07)	-0.846 (2E-07)	-0.442 (2E-07)
GARI					-0.484 (2E-07)	0.864 (2E-07)	0.804 (2E-07)	0.885 (2E-07)	0.864 (2E-07)	0.565 (2E-07)
iron						-0.063 (0.041)	-0.463 (2E-07)	-0.322 (2E-07)	-0.063 (0.041)	-0.965 (2E-07)
NDVI							0.699 (2E-07)	0.855 (2E-07)	1.000 (2E-07)	0.198 (1.05E-10)
NDWI 6								0.936 (2E-07)	0.699 (2E-07)	0.576 (2E-07)
NDWI 7									0.855 (2E-07)	0.438 (2E-07)
SAVI										0.198 (1.04E-10)
VARIgreen										

Top no=correlation coefficient r, bottom no=p value, clay= clay minerals, ferr.6= ferrous minerals using band 6, ferr.7= ferrous minerals using band 7, GARI .1= Green Atmospherically Resistant index using band 1, iron= iron oxide, NDVI =Near Difference Vegetation Index, NDWI.6= Near Difference Water Index using band 6, NDWI.7= Near Difference water Index using band 7, SAVI= Soil Adjusted Vegetation Index, VARIgreen.1= Visible Atmospherically Resistant Index using band 1.

Table 3.5 Candidate mixed models and their related statistics, describing forage locations of the sable woodland herd in Kgaswane Mountain Reserve, based on satellite indices generated from Landsat 8

No.	Model	Fixed effects	AICc	△AICc	Wi(AICc)	df
1	1sw	1sw: locations~clay	668.58	0	0.97	1142
4	4sw	4sw: locations~gari 1	675.72	7.14	0.03	1142
8	8sw	8sw: locations~ndwi 7	679.23	10.65	0.00	1142
6	6sw	6sw: locations~ndvi	684.37	15.79	0.00	1142
9	9sw	9sw: locations~savi	684.37	15.79	0.00	1142
3	3sw	3sw: locations~ferr 7	684.70	16.11	0.00	1142
11	11sw	11sw:locations~ndvi+iron	685.35	16.77	0.00	1142
12	12sw	12sw:locations~savi+iron	685.35	16.77	0.00	1142
7	7sw	7sw: locations~ndwi 6	689.29	20.7	0.00	1142
10	10sw	10sw: locations~varigreen 1	691.33	22.75	0.00	1142
2	2sw	2sw: locations~ferr 6	693.21	24.63	0.00	1142
13	nullmodel	locations~1	694.21	25.63	0.00	1142
5	5sw	5sw: locations~iron	695.17	26.59	0.00	1142

AICc Akaike's= Information Criterion adjusted for smaller samples, △ AIC= change in index value between T_n and T_{n-1}, Wi (AICc) = rounded AIC weights, df degrees of freedom.

The second best model was model 4sw (locations ~ GARI), which however only had △AIC of 7.14 and a weight of 3%. Therefore the variable with the most accumulative weight is clay minerals (0.97), followed by GARI (0.03) (Table 3.3). The sable woodland herd was using areas with lower clay minerals compared to what was available at random non-used locations (Figure 3.6 a), and was also using areas with lower GARI than what was available, although the contribution of this index is negligible compared to that of clay minerals (Figure 3.6 b).

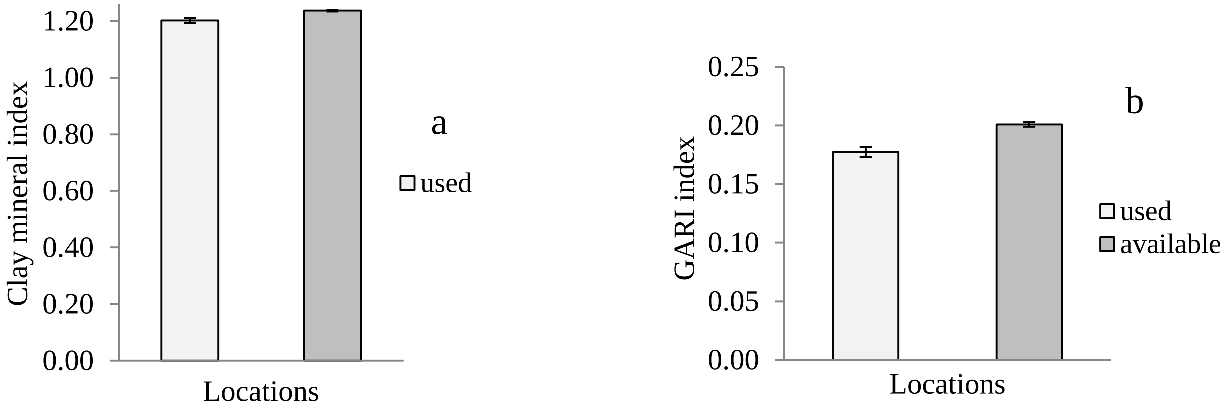

Figure 3.6 Indices values for used versus available locations for sable woodland herd, a) clay mineral, b) GARI. The error bars show the standard error.

Eland herd

For the eland herd most indices were correlated (Table 3.6), so I ran models for each of the indices separately, and included six additive models (clay + ferr 6; clay + NDWI 6; NDVI + iron; SAVI + iron; NDVI + VARIgreen and SAVI + VARIgreen). The best model to fit the AICc criteria for the eland herd was model 5e (locations ~ iron) with weight of 25% probability of being the best model. This model depicts the relationship between the predictor iron oxide and the response variable (Table 3.7). Other top candidate models were models 11e (locations ~ NDVI + iron) showing the sum of the individual effects of the predictor variables NDVI and iron oxide on the response variable; and model 12e (locations ~ SAVI + iron) with SAVI substituting NDVI. These two models have the accumulative weight of 24%. I also included model 10e (locations ~ VARIgreen) with a weight of 8% and model number 16e (locations

~ clay + NDWI 6) with a weight of 6 % (Table 3.7). The rank factors showing variables with the most accumulative weights are iron oxide (0.49), the only variable with weight > 2, followed by NDVI (0.17), SAVI (0.17), clay minerals (0.14) and VARIgreen (0.14), and NDWI 6 (0.11) (Table 3.3).

Table 3.6 Eland herd correlation results for indices. The non-significant correlations are shown in grey

	clay	ferr 6	ferr 7	GARI	iron	NDVI	NDWI 6	NDWI 7	SAVI	VARIgreen
clay		-0.055 (0.382)	-0.490 (2E-07)	0.526 (2E-07)	0.302 (1.13E-06)	0.716 (2E-07)	0.122 (2E-07)	0.490 (2E-07)	0.716 (2E-07)	-0.235 (1.72E-4)
ferr 6			0.775 (2E-07)	-0.561 (2E-07)	0.328 (1.15E-07)	-0.457 (2E-07)	-0.885 (2E-07)	-0.775 (2E-07)	-0.457 (2E-07)	-0.539 (2E-07)
ferr 7				-0.819 (2E-07)	0.194 (1.93E-3)	-0.777 (2E-07)	-0.900 (2E-07)	-1.000 (2E-07)	-0.777 (2E-07)	-0.409 (2E-07)
GARI					-0.329 (1.01E-07)	0.817 (2E-07)	0.663 (2E-07)	0.819 (2E-07)	0.817 (2E-07)	0.475 (2E-07)
iron						0.111 (0.0782)	-0.344 (2.33E-08)	-0.194 (0.00193)	0.111 (0.0782)	-0.813 (2E-07)
NDVI							0.545 (2E-07)	0.777 (2E-07)	1.000 (2E-07)	0.0741 (0.240)
NDWI 6								0.9000 (2E-07)	0.545 (2E-07)	0.566 (2E-07)
NDWI 7									0.777 (2E-07)	0.409 (1.71E-11)
SAVI										0.074 (0.240)
VARIgreen										

Top no=correlation coefficient r, bottom no=p value, clay= clay minerals, ferr.6= ferrous minerals using band 6, ferr.7= ferrous minerals using band 7, GARI .1= Green Atmospherically Resistant index using band 1, iron= iron oxide, NDVI =Near Difference Vegetation Index, NDWI.6= Near Difference Water Index using band 6, NDWI.7= Near Difference water Index using band 7, SAVI =Soil Adjusted Vegetation Index, VARIgreen.1= Visible Atmospherically Resistant Index using band 1.

Table 3.7 Candidate mixed models and their related statistics, describing forage locations of eland herd in Kgaswane Mountain Reserve, based on satellite indices generated from Landsat 8.

No.	Model	Fixed effects	AICc	△AICc	Wi(AICc)	df
5	5e	locations~iron	152.36	0	0.25	252
11	11e	locations~ndvi+iron	153.76	1.4	0.12	252
12	12e	locations~savi+iron	153.76	1.4	0.12	252
10	10e	locations~varigreen 1	154.60	2.24	0.08	252
16	16e	locations~clay+ndwi6	154.92	2.55	0.07	252
4	4e	locations~gari 1	155.26	2.9	0.06	252
1	1e	locations~clay	155.91	3.55	0.04	252
7	7e	locations~ndwi 6	156.16	3.8	0.04	252
17	nullmodel	locations~1	156.19	3.82	0.04	252
15	15e	locations~clay+ferr6	156.46	4.1	0.03	252
13	13e	locations~ndvi+varigreen1	156.63	4.27	0.03	252
14	14e	locations~savi+varigreen1	156.63	4.27	0.03	252
2	2e	locations~ferr 6	157.23	4.87	0.02	252
6	6e	locations~ndvi	157.60	5.24	0.02	252
9	9e	locations~savi	157.60	5.24	0.02	252
8	8e	locations~ndwi 7	157.97	5.61	0.02	252
3	3e	locations~ferr 7	158.15	5.79	0.01	252

AICc Akaike's= Information Criterion adjusted for smaller samples, △ AIC= change in index value between T_n and T_{n-1}, Wi (AICc) = rounded AIC weights, df degrees of freedom.

The eland were using areas with slightly lower iron oxide than what was randomly available (Figure 3.7 a). They were using areas with higher NDVI, SAVI and VARIgreen values compared to what was available (Figure 3.7 b, c and d). Similar to the sable woodland herd, which is found in the same area, they were avoiding areas with clay minerals (Figure 3.7 e). They were also using locations with higher NDWI 6 (Figure 3.7 f) compared to non-used locations.

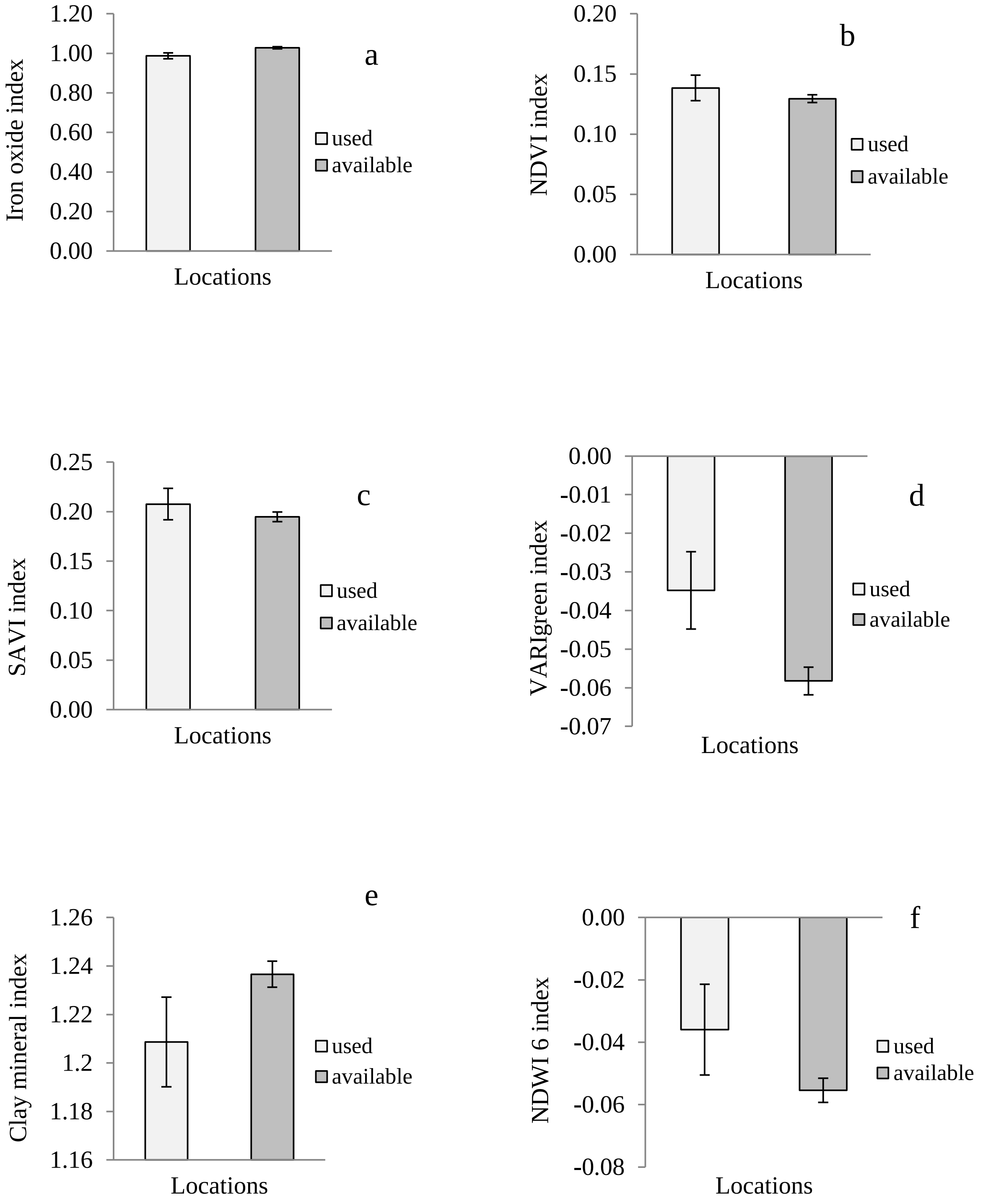

Figure 3.7 Indices values for used versus available locations for eland a) iron oxide, b) NDVI, c) SAVI, d) VARIgreen, e) clay minerals, f) NDWI 6. The error bars show the standard error.

Discussion

Dry season locations from two herds of sable antelope and one herd of eland in KMR were used to test if there is an index or combination of indices that serve as a better indicator of animal distribution than NDVI alone. Further indices representing other factors besides vegetation chlorophyll content as measured by NDVI were calculated from Landsat 8 bands. These indices may improve the understanding of animal locations within the landscape.

The sable vlei herd was linked to locations that have higher NDVI and SAVI values than what was otherwise available. SAVI corrects for ‘noise’ caused by brightness of the reflectance from the soil component (Huete *et al.* 1985; Najeeb 2013). VARIgreen was also associated with NDVI and SAVI. This atmospherically sensitive greenness index compensates for the effect of aerosol scattering of red light. When red band reflectance is increased, NDVI values decrease and VARIgreen will be a more reliable indicator of greenness (Holben 1986). During the dry season there may be intensified atmospheric pollution due to veld fires and domestic fires from the nearby town of Rustenburg, which could explain why an atmospherically sensitive index, in addition to NDVI or SAVI, comes up as a suitable indicator of animal location. The fact that VARIgreen has a negative value indicates high levels of atmospheric aerosols (Jackson *et al.* 1983; Jackson and Huete 1991).

The sable vlei herd was located on the grassland plateau, which has a relative uniformity in vegetation type and a lack of trees (Chapter 2). Selectivity for greenness by sable antelope is supported by previous studies (Parrini 2006; Le Roux 2010; Mokoena 2012), which have addressed resource selection at finer scales than the scale of this study. For example during the dry season, sable selected the greenest tufts they could find, even accepting grass species they would not necessarily tolerate during the wet season (Parrini 2006; Le Roux 2010; Mokoena 2012) and even if they had to travel to areas that still retained greenness (Parrini 2006). Post-burn regrowth is often grazed as it has higher greenness values than surrounding unburned areas, although the amount of vegetation biomass will initially be lower in the burned than unburned areas (Parrini and Owen-Smith 2010). However, during the study period the vlei herd made little use of burnt areas (Chapter 2). As this study was conducted in the dry season, greenness values were assumed to be the consequence of grasses remaining green because of their position in the landscape such as drainage lines, wetlands or riverine areas (Anderson and Kneale 1980); or because of underlying soil types such as clay, which retain moisture for longer periods (Scoones 1991). The central vlei area on the plateau of KMR is a wetland containing the clay-rich Hutton, Oakleaf and Kroonstad soil forms (Nel 2000). Therefore this region contains greener vegetation for longer periods into the dry season. However the locations for the sable vlei herd were seldom in the central vlei area, even though they were selecting areas with higher greenness values than what was available to them as indicated by NDVI, SAVI and VARIgreen.

The sable vlei herd was found to be associated with locations that have lower iron oxide values compared to what was available. This makes sense as the Transvaal Sequence, made up of Magaliesberg Quartzite, lies beneath the plateau where the herd is found (Chapter 2). Quartzite contains very low quantities of ferrous minerals and iron oxide as it is a primary mineral containing no weatherable minerals, such as iron (Palm *et al.* 2007). As the vlei herd was located most frequently in areas underlain by Glenrosa and Mispah soil forms (Chapter 2), it appears to be using areas with less iron oxide than are available elsewhere on the reserve. However this might not necessarily mean that sable antelope are avoiding areas with high iron oxide. Other factors that have not been included in this study could be influencing their use of areas that happen to have low amounts of iron oxide but this cannot be validated using Landsat imagery as the scale is not fine enough to determine iron within grass.

The clay mineral index was the best indicator describing the locations of the woodland sable herd. This herd was located mainly in areas with lower clay content than what was available elsewhere, which contradicts the premise that during the dry season they would be seeking clay-rich areas with greater water retention capacity and therefore greener vegetation (Scoones 1995). However clay-rich soils are not automatically associated with the capacity to sustain moisture into the dry season (Farrar *et al*. 1994). Various characteristics such as soil moisture tension, texture, porosity, nutrients and chemical composition should also be taken into account when determining soil moisture availability and therefore the type of vegetation growth supported by the soil (Farrar *et al*. 1994). A possible explanation is that during the study period the woodland herd was often located within a post-burn green flush and the vegetation communities that were burnt are underlain by a shallow, coarse-grained and sandy variation of the Glenrosa soil form (Chapter 2). Thus, although varieties of the Glenrosa soil form, especially those found in low-lying areas accumulate clay (Nel 2000), there was little clay where the sable antelope locations were recorded, compared to what was available in the rest of their home range.

The woodland herd was found in areas with lower greenness levels than what was available to them. This was indicated by GARI, a greenness index that adjusts for interference from atmospheric pollutants. In a study done by Kaonga and Kgabi (2011), it was shown that airborne particulate matter in Marikana, Rustenburg, was higher in the early morning (06h00 to 09h00); again at midday (12h00 to 15h00); and in the early evening (15h00 to 18h00) due to mining, industrial, traffic and domestic pollutants. These times coincide with the time that the images were taken (around 0h800 to10h14 Greenwich Mean Time), and also with the foraging times that were recorded for the sable antelope. In winter this could be more severe in the early morning and the late afternoon due to the formation of a thermal inversion layer, whereby the temperature of ascending air decreases for some meters into the atmosphere before warming up and becoming constant (Anquetin *et al.* 1998). The cooler air is effectively trapped below the inversion layer, and with it any form of aerosol pollutant (Anquetin *et al.* 1998). GARI has an improved capacity to measure chlorophyll levels and is less sensitive to atmospheric effects than NDVI (Gitelson *et al.* 1996). Under these circumstances it is understandable how an atmospherically corrected index could outperform NDVI. However it must be remembered that the possibility of GARI being an important variable was minimal compared to the clay mineral variable.

As sable antelope are grazers, they would be expected to be selecting grasses even in the woodland-grassland matrix. In woodlands the biomass measured by greenness indices would mostly be represented by trees, especially in the dry season when grass would be in a state of senescence with evergreen trees providing the highest greenness values (Borchert 1999). However sable antelope would be seeking grass patches, or post-burn green flushes, which would have lower greenness values and would represent lower biomass relative to the surrounding tree cover (Zinn 2013). The area available to the woodland herd is characterised by both closed and open woodland, with open woodland being a preferred habitat for sable antelope (Chapter 2). This suggests that the use of a greenness index can be problematic in areas with intermingled trees and grasses as it might give misleading results. So the woodland herd appears to be avoiding greenness when in fact this may just be a result of them selecting areas with the greenest grasses still available, which would have lower greenness values compared to trees in the woodland communities.

The fact that the woodland herd was located in areas with lower greenness than what was available is contrary to what was observed for the vlei herd. The vlei herd was positively selecting for greenness as the satellite images were of homogenous open grassland, where both used and available areas are comparable from the aspect of vegetation cover. An alternative explanation for the negative selection of greenness by the woodland herd could be that the locations of the woodland herd were mostly within burnt areas (Chapter 2). It would appear that due to the low biomass of new plant regrowth in a burnt area (Van der Vijver *et al.* 1999; Snyman 2009; Allred *et al*. 2011) the greenness values may still be lower than that of tree foliage; but not of unburned taller grass during the dry season (Rahman and Gamon 2004).

During the period of this study the eland herd remained in the lowlands as in the dry season they potentially limit their range (Hillman 1988). The area utilised by the eland was similar to that of the woodland sable herd. However the eland were located more often in closed woody areas with higher green biomass, but also in open woodlands that are preferred by the sable antelope (Chapter 2). This supports the fact that eland will seek out areas with the greenest vegetation, represented by the tree component of woodlands (Jarman 1972; Field 1975; Estes 1991). Eland are known to browse during the dry season when resources are scarce (Buys and Dott 1991; Estes 1991; D’Ammando *et al*. 2015). Consequently they were found in areas with high greenness values.

In this study NDVI and SAVI appear to be interchangeable and are suitable indicators of green biomass. NDVI values can fluctuate in the dry season when vegetation ground cover is reduced and underlying soil is exposed, which weakens their reliability (Najeeb 2013) so by adding SAVI the usefulness of the results may improve. Moreover, in areas that may be partial to atmospheric pollution NDVI and SAVI could benefit by including an atmospherically sensitive vegetation index, as aerosol scattering can alter NDVI results (Holben 1986). For both the sable vlei herd and the eland herd NDVI and SAVI are associated with VARIgreen, which seems to enhance them by correcting for airborne pollution. In a study conducted to analyse the effects of both soil reflectance and atmospheric conditions on NDVI, Huete and Jackson (1988) found that in partially vegetated canopies, soil brightness and atmospheric turbidity affected the values of vegetation indices such as NDVI. When soil reflectance was high, the atmospheric effects were low, but where the atmosphere was more turbid, soil reflectance effects weakened. Therefore higher or lower vegetation index values may be partly the outcome of green biomass; but could also be because of the stage of plant growth, atmospheric turbidity, the angle of the sun in its zenith, and exposed surface soil conditions (Jackson *et al*. 1983; Huete and Jackson 1988).

Another reason supporting the fact that eland are seeking out woody areas is because their locations were positively described by NDWI. This index measures water content in vegetation and can be used as a proxy to indicate soil moisture (Gao 1996; Loyd *pers. comm.* 2014). This can be biologically explained by the fact that in the dry season trees can store more water and nutrients and their leaves contain more moisture than dormant grasses (Archibald and Scholes 2007) and the sub-canopy microclimate beneath trees is generally more humid than surrounding open vegetation areas (Ludwig *et al.* 2004). In the case of this study, the eland herd was found within homogenous vegetation communities such as closed woodlands and in heterogeneous open woodlands, where they could browse. However they also frequently grazed the post-burn green flush in open woodland. They were positively selecting both NDVI and NDWI. These vegetation communities probably had higher soil moisture than the drier unburnt vegetation communities surrounding them.

As with the woodland sable herd, the eland herd avoided areas with high clay mineral values, and to a less extent, iron oxide. The areas where the eland were located were not necessarily clayey (Chapter 2) and in fact there are few areas with a high clay content in the dominantly norite rocks found in the region, but due to the norite substratum they are rich in iron (Norman and Whitfield 2006). However, for just under half the locations recorded, the eland appeared to make use of a post-fire green flush in a vegetation community growing on shallow soils of the Glenrosa form, overlying a geological template consisting of a mixture of iron-rich norite and infertile quartzite (Chapter 2). Possibly the quartz - norite combination could dilute the concentration of iron oxide compared to that in the pure norite rocks found in the majority of this area. The rest of the eland locations were situated in closed woodland vegetation communities growing on iron-rich norite rocks (Chapter 2).

Conclusion

The outcome of the study is that NDVI is a sufficient indicator of distribution for both grazers and browsers in homogenous landscapes. NDVI values can be improved by the inclusion of additional greenness indicators; but probably the importance of these would depend on the location of the environment in question and also the time of the year.

NDVI (or possibly any greenness index) is not a good indicator for grazers in a heterogeneous woodland matrix, especially during the dry season, when greenness as measured by NDVI predominantly represents trees and shrubs. In such areas grazers appear to be negatively selecting for NDVI, whereas they are more than likely searching for vestiges of green grass within patches of dry, dormant grassland amongst trees. In the same general area, both greenness and soil moisture are good indicators for browser location because during dry months trees will hold more moisture within their leaves and retain more greenness than grasses (Field 1975).

Although the presence of clay minerals and therefore soil nutrients appeared to be an important indicator for animals located in the lowlands, this was confounded by the presence of a post-burn green flush, which was opportunistically grazed by both the sable and eland herds. The green flush was in a vegetation community underlain by soil with less clay, and bedrock with less iron than in surrounding available areas. Had this burn not occurred, it is possible that other variables would have better described the animals' distribution within the landscape. The importance of iron oxide as an indicator of animal location is simplistically explained by the geological template and soil type underlying the preferred vegetation communities used by the sable vlei and eland herds; but difficult to infer biologically at the scale of Landsat imagery.

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CHAPTER 4 CONCLUSION AND SYNOPSIS

Synthesis

With regards to the aim of this study, NDVI greenness values described animal locations for the sable vlei herd and the eland herds, but not for the sable woodland herd. For the sable vlei herd on the grassland plateau and the eland herd situated in woodlands, it was found that similar greenness indices (NDVI, SAVI and VARIgreen) were consistent in homogeneous vegetation constructs such as grasslands and closed woodlands even though the grassland was on the highland plateau and the woodland was in the lowlands at the base of the mountains. SAVI corrects for soil reflectivity (Huete 1988) and proved to be an equally effective indicator of animal location as NDVI. These two indices were associated with VARIgreen. Atmospherically sensitive indices such as VARIgreen and GARI are both at an advantage in the presence of aerosol pollutants generated by the close proximity of an urban and industrial area (Xiao *et al.* 2003).

The sable woodland herd was in the same vicinity as the eland herd, but was grazing in heterogeneous open woodlands. They were located in areas with lower greenness values as indicated by GARI than what was available to them. Sable antelope prefer open woodlands (Jarman 1972; Wilson & Hirst 1977); selecting residual greenness in dormant grasses (Parrini 2006; Owen-Smith *et al.,* 2013) or in green flushes (Parrini and Owen-Smith 2010). These areas have lower greenness values than the adjacent woody vegetation. This suggests that in a woodland matrix, greenness values could be ambiguous when evaluating the ecology of a grazing herbivore. However, as a suitable indicator of animal location, GARI proved to be negligible compared to the clay mineral variable.

Additional indices that represent different ecological factors other than greenness enhanced the ability of NDVI to describe animal locations within the landscape. Eland were found in areas with higher soil moisture than what was available, shown by NDWI. The mineral composite indices used in this study have enriched the interpretation of animal locations in the environment. Including these indices has helped clarify that although the sable vlei herd and eland herds were positively selecting greener areas; these areas were not necessarily linked to soil moisture found in clay. For the sable vlei herd, this is incongruous due to the presence of the clay-rich soils of the wetland, but the sable were not often located in the wetland and appeared to be finding green vegetation elsewhere. Clay minerals was an important variable for both the eland and the sable woodland herd, but this was basically because they were both utilising a post-burn green flush that consisted of vegetation communities located on clay-poor soils compared to what was available. Therefore the avoidance of areas with clay minerals was possibly just a reflection of the opportunistic utilisation of new vegetation growth by different herbivore species within an area poor in clay.

The sable vlei herd and the eland herd commonly avoided areas with iron oxide. The sable vlei herd was situated in an area with a geological template low in iron-rich rocks (Norman and Whitfield 2006), but reasons for the avoidance of areas with iron oxide by the eland herd are more obscure. Possibly this is due to the fact that many of the eland locations were within a post-burn green flush in vegetation communities overlying a mixture of quartz and norite that has a diluted amount of iron compared to the surrounding pure norite rocks in the area.

Therefore, although NDVI remains a good indicator of greenness, it can be enhanced or replaced by alternative greenness indices. Moreover indices representing other aspects of ecology can improve or even surpass NDVI in the explanation of animal locations within the landscape, but this depends on the local environment and the animal species being studied. Indices either overlap or fluctuate between different habitats and different herbivore species; subject to the specific geological and biological situation of both the animals' location within the environment and their particular physiological needs. It is possible that indices would differ seasonally, but this study only described the dry season and a green flush was fortuitously present for two of the herds, which would not always be the case. Consequently these results would probably not be transferable to other species or other habitats with different environmental influences and needs and over different time periods.

Conclusions

This study set out to describe ecological characteristics of the study area in order to interpret whether there was an indicator or group of indices that could improve on the use of NDVI alone in understanding large herbivore location within the landscape; and to test whether this could be remotely derived from Landsat 8. Overall NDVI is a good indicator for grazers in homogenous grasslands and also for mixed feeding browsers in closed woodlands, but not for grazers in a heterogeneous woodland matrix. Therefore it is recommended that as a general indicator of animal location within the environment, NDVI is adequate; and depending on the area of interest, the season, and the species of animal to be studied, other indices can be included to enhance NDVI results.

Further studies could be conducted using the same animal species but in different environments, such as areas remote from urban influences, or areas containing different biomes; to see how satellite indices that describe animal locations would change due to variations in local biotic and abiotic factors. Also comparisons could be made between the outcomes of Landsat NDVI values versus NDVI values of another satellite platform, such as MODIS, which would include an improved temporal scale, although the spatial resolution would be compromised. Therefore there needs to be a trade-off between spatial and temporal resolution. A potential future study should analyse this trade-off and interrogate what combination might work best (high spatial resolution but low temporal resolution or low spatial resolution but high temporal resolution). The answer most likely will depend on the question being addressed and the species under investigation.

Limitations of the study

The study was only done during the dry season. The inclusion of the wet season would have been preferential, as more comprehensive information may have emerged with regards to the values of the indices tested; but there were only two Landsat images during the wet season that were clear enough of cloud cover to extract data. Therefore the wet season had to be omitted. The course temporal scale of 16 days (Loyd 2013) limits Landsat imagery in that it represents only one instance in time, unlike MODIS with a temporal scale of one flyover a day, which allows composite images of 16 days to be built, thus correcting for data omissions caused by cloud cover (Engel-Cox *et al.,* 2004; CEO 2010). Also the presence of the large burn caused by a runaway fire could have altered the foraging patterns of both the sable woodland herd and the eland herd during the study period, so including a further dry season in the study may have achieved different results with regards to the satellite indices that best explained animal distribution.

The fact that animals were located in areas with less clay that what was available is inconsistent with most literature, which states that during the dry season animals are drawn towards areas that sustain green foliage for longer periods (Anderson and Kneale 1980; McNaughton 1985; Scoones 1991), such as areas underlain with clay soils that have high mineral content and soil moisture (Scoones 1995). At the spatial scale of Landsat 8 imagery it was hard to infer a biological explanation for this contradiction. It was also difficult to explain why eland, who were browsing in vegetation communities underlain by iron-rich soils, would be avoiding areas with iron oxide, except for the fact that they also often grazed in burnt vegetation communities where there was less iron oxide in the soil compared to surrounding areas. It is possible that the explanation for these inconsistencies could be found using both a finer spatial scale and a finer spectral bandwidth than what is available on Landsat 8.

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APPENDICES

Appendix I Landsat 8 Imager Spectral Bands: Resolutions and Uses. Adapted from ESA (2013) and USGS (2013).

Band number	Band name	Spectral range (μm)	Use of data	Resolution (m)
1	New deep blue	0.43-0.45	Aerosol/coastal zone	30m
2	Blue	0.45-0.51	Bathymetric mapping/distinguish soil from vegetation/ coniferous from deciduous	30m
3	Green	0.53-0.59	Peak vegetation to assess plant vigour	30m
4	Red	0.64-0.67	Vegetation slopes	30m
5	NIR	0.85-0.88	Foliage/vegetation boundary between land and water/landforms	30m
6	SWIR 1	1.57-1.65	Foliage/plant drought stress/burnt areas/thermal radiation of fires/detect active fires	30m
7	SWIR 2	2.11-2.29	Minerals/litter/no scatter/drought stress/detecting active fires	30m
8	PAN	0.50-0.68	Image sharpening	15m
9	SWIR cirrus	1.36-1.38	Cirrus cloud detection	30m
10	TIRS 1	10.60 – 11.19	Mapping thermal differences in Earth’s surface, water currents, monitoring fires, estimating soil moisture	100m
11	TIRS 2	11.50-12.51	Same as band 10	100m

NIR = near infrared, SWIR = shortwave infrared, PAN = panchromatic band, TIRS = thermal infrared.

Appendix II Dates and codes for each 16-day Landsat 8 flyover period during the study period (June 2013 – September 2014).

Time Period (for sable vlei herd)	Image Number	Dates
1	2013196	15/7/2013
2	2013212	31/7/2013
3	2031228	16/8/2013
4	2013244	1/9/2013
5	2013260	17/9/2013
6	2013292	19/10/2013
7	2014135	15/5/2014
8	2014151	31/5/2014
9	2014167	16/6/2014
10	2014199	18/7/2014
11	2014215	3/8/2014
12	2014247	4/9/2014
Time Period (for sable woodland and eland herds)	**Image Number**	**Dates**
1	2013196	15/7/2013
2	2013212	31/7/2013
3	2031228	16/8/2013
4	2013244	1/9/2013
5	2013260	17/9/2013
6	2013292	19/10/2013
7	2014135	15/5/2014
8	2014151	31/5/2014
9	2014167	16/6/2014
10	2014199	18/7/2014
11	2014215	3/8/2014
12	2014247	4/9/2014

Appendix III Used and non-used vegetation communities within the sable vlei, sable woodland and eland herd's available area, grass species within each community and number of times each community was used (Sources: Forage species information from Nel 2000; Parrini 2006; Pappas 2002; Wallington *et al.* 2007; D'Ammando *et al.* 2015).

Vegetation communities available to the sable vlei herd	**Grasses acceptable to sable antelope**	**No. of locations**
Burkea africana- Setaria sphacelata tall open woodland	*Setaria sphacelata, Trachypogon spicatus*	19
Croton grastissimus- Combretum molle short open woodland	*Diheteropogon amplectens*	13
Lopholaena coriifolia- Lapeirousia sandersonii short open grassland	*Themeda triandra, T. spicatus, Schizachyrium sanguineum, D. amplectens*	10
Trachypogon spicatus- Sphenostylis augustifolia tall closed grassland	*Tristachya biseriata, T. spicatus, D. amplectens, T. triandra*	7
Indigofera comosa- Schizachyrium sanguineum tall closed grassland	*S. sanguineum, D. amplectens, T. triandra, T. spicatus*	6
Ruellia patula- Melinus nerviglumis short open woodland	*D. amplectens, T. biseriata, S. sphacelata, Heteropogon contortus, T. triandra*	6
Ceterach cordatum- Tristachya leucotrix tall sparse shrubland	*T. spicatus*	5
Protea gaguedi- Monocymbium ceresiiforme short open shrubland	*Tristachya rehmannii, T. spicatus, D. amplectens, T. triandra*	5
Heteropogon contortus- Faurea saligna tall open woodland	*H. contortus, S. sphacelata, T. triandra*	3
Aristida junciforms- Arundinella nepaliensis tall closed grassland	-	2
Aloe greatheadii- Themeda triandra tall open woodland	*S. sphacelata, T. triandra, T. spicatus, D. amplectens*	1
Asparagus krebsianus- Senecio venosus high open shrubland	*S. sanguineum, D. amplectans, T. triandra*	1
Blumea alata- Parinari capensis short sparse woodland	*T. biseriata,Panicum natalensis, S. sanguineum, T. triandra*	1
Indigofera burkeana- Rhynchosia totta short closed woodland	*T. biseriata,T. triandra, T. spicatus*	1
Pteridium aquilinum- Miscanthus junceus tall closed grassland	-	1

Becium obovatum- Protea caffra tall closed woodland	*H. contortus*	1
Aristida transvaalensis- Bulbostylis burchellii tall sparse shrubland	-	-
Asparagus virgata- Celtis africana tall closed woodland	*Panicum maximum, Setaria megaphylla*	-
Brachylaena rotundata- Englerophytum magalismontanum high open shrubland	*Loudetia simplex, T. spicatus, D. amplectens, S. sanguineum, Tristachya bisetaria*	-
Cheilanthes viridus- Combretum molle short open woodland	*H. contortus*	-
Digitaria eriantha- Lippia javanica tall closed woodland	-	-
Diheteropogon amplectens- Ficinia filiformis short closed woodland	*T. bisetaria, L.simplex, P. natalensis, D amplectens, T. triandra,T. spicatus,Brachiaria serrata*	-
Diospyros lycioides- Cymbopogon validus tall sparse shrubland	*S. sanguineum, D. amplectens*	-
Euclea crispa- Panicum maximum tall closed woodland	*P. maximum, T. triandra*	-
Faurea saligna- Cyperus sphaerosermus short open woodland	*T. triandra, B. serrata*	-
Loudetia flavida- Tristachys biseriata tall closed shrubland	*T. bisetaria, T. spicatus, L. simplex, S. sanguineum, D. amplectens, T. triandra, B. serrata*	-
Mimussops zeyheri- Hypoetes forskaoli tall forest	-	-
Olea europaea- Grewia occidentalis tall closed woodland	*P. maximum*	-
Plexipus hederaceus- Cymbopogon excavatus tall closed grassland	*D. amplectens, T. triandra, T. spicatus*	-
Senecio venosus- Heteropogon contortus tall closed woodland	*S. sphacelata, H. contortus, T. triandra, P. maximum*	-
Themeda triandra- Eragrostis racemosa short open grassland	*T. triandra, D. amplectens, B. serrata*	-
Trachypogon spicatus- Bulbostylis burchellii short sparse woodland	*T. spicatus, D. amplectens, T. triandra, B. serrata*	-

Vegetation communities available to the sable woodland herd	**Grasses acceptable to sable antelope**	**No. of Locations**
Heteropogon contortus- Trachypogon spicatus tall open woodland	*H. contortus, T. spicatus, T. triandra*	28
Trachypogon spicatus- Bulbostylis burchellii short sparse woodland	*T. spicatus , D. amplectens, T. triandra*	25
Heteropogon contortus- Faurea saligna tall open woodland	*H. contortus, S. sphacelata, T. triandra*	9
Asparagus virgata- Celtis africana tall closed woodland	*P. maximum*	8
Setaria sphacelata- Themeda trianda tall closed woodland	*S. sphacelata, H. contortus, T. triandra, P. maximum*	6
Loudetia flavida- Tristachys biseriata tall closed shrubland	*T. biseriata, T. triandra, T. spicatus, S. sanguineum, D. amplectens*	3
Burkea africana- Setaria sphacelata tall open woodland	*S. sphacelata*	3
Senecio venosus- Heteropogon contortus tall closed woodland	*S. sphacelata, H. contortus, T. triandra, P. maximum*	2
Trachypogon spicatus- Sphenostylis augustifolia tall closed grassland	*T. biseriata, T. spicatus, T. triandra, D. amplectens*	2
Aristida transvaalensis- Bulbostylis burchellii tall sparse shrubland	-	1
Aristida junciforms- Arundinella nepaliensis tall closed grassland	-	-
Asparagus krebsianus- Senecio venosus high open shrubland	*S. sanguineum, T. triandra, D. amplectens*	-
Blumea alata- Parinari capensis Tall closed woodland	*T. biseriata, Panicum natalensis, S. sanguineum, T. triandra*	-
Brachylaena rotundata- Englerophytum magalismontanum high open shrubland	*L. simplex, T. spicatus, D. amplectens, S. sanguineum, T. biseriata*	-
Ceterach cordatum- Tristachya leucotrix tall sparse shrubland	*T. spicatus*	-
Cheilanthes viridus- Combretum molle short open woodland	*Eustachys paspaloides, H. contortus*	-
Croton grastissimus- Combretum molle short open woodland	*D. amplectens*	-
Cryptolepis oblongifolia- Loudetia simplex tall sparse woodland	*L. simplex, P. natalensis, S. sanguineum, D. amplectens, Bewsia biflora, T. triandra, T. spicatus, Brachiaria serrata*	-

Digitaria eriantha- Lippia javanica tall closed woodland	*Sporobolus fimbriatus*	-
Diheteropogon amplectens- Ficinia filiformis short closed woodland	*T. biseriata, L. simplex, P. natalensis, D. amplectens, T. triandra, T. spicatus, B. serrata*	-
Euclea crispa- Panicum maximum tall closed woodland	*P. maximum, T. triandra, Setaria nigrirostris*	-
Indigofera comosa- Schizachyrium sanguineum tall closed grassland	*S. sanguineum, D. amplectens, T. triandra, T. spicatus*	-
Lopholaena coriifolia- Lapeirousia sandersonii short open grassland	*T. triandra, T. spicatus, S. sanguineum, D. amplectens*	-
Mimussops zeyheri- Hypoetes forskaoli tall forest	-	-
Olea europaea- Grewia occidentalis tall closed woodland	*P. maximum, T. biseriata, Setaria megaphylla*	-
Pteridium aquilinum- Miscanthus junceus tall closed grassland	-	-
Ruellia cordata- Senecio venosus tall sparse woodland	*Tristachya luecotrix, S. sphacelata, H. contortus, T. triandra, T. spicatus, B. serrata*	-
Ruellia patula- Melinus nerviglumis short open woodland	*D. amplectens, T. biseriata, Setaria sphacelata, H. contortus, T. triandra*	-
Tagetes minuta- Commelina africana sparse open woodland	*Cynodon dactylon, P. maximum*	-

Vegetation communities available to the eland herd	**Plant species acceptable to eland**	**No. of Locations**
Heteropogon contortus- Faurea saligna tall open woodland	Tree: *Faurea saligna*	6
	Grasses: *S. sphacelata, T. triandra*	-
Pteridium aquilinum- Miscanthus junceus tall closed grassland	Forb: *Helichrysum setosum*	2
Ruellia cordata- Senecio venosus tall sparse woodland	Trees: *F. saligna, Combretum zeyheri, Combretum molle*	2
	Grasses: *S. sphacelata, T. triandra*	-
Euclea crispa- Panicum maximum tall closed woodland	Trees: *Ziziphus mucronata, C. zeyheri, Rhus leptodictya, C. molle, Dombeya rotundifolia*	1
	Shrub: *Lippia javanica*	-
	Grasses: *P. maximum, T. triandra*	-
Heteropogon contortus- Trachypogon spicatus tall open woodland	Trees: *F. saligna*	1
	Grass: *T. triandra*	-
Lopholaena coriifolia- Lapeirousia sandersonii short open grassland	Grass: *T. triandra*	1
Olea europaea- Grewia occidentalis tall closed woodland	Trees: *Z. mucronata, Combretum erythrophyllum, Rhus pyroides, D. rotundifolia,*	1
	Diospyros Lycioides.	-
	Shrub: *Asparagus cooperi*	
Senecio venosus- Heteropogon contortus tall closed woodland	Trees: *F. saligna, D. rotundifolia*	1
	Grasses: *T. triandra, P. maximum*	-
Setaria sphacelata- Themeda trianda tall closed woodland	Trees: *L. javanica, C. zeyheri, R. leptodicta, Acacia caffra, Z. mucronata*	1
	Grasses: *S. sphacelata, T. triandra, P. maximum*	-
Tagetes minuta- Commelina africana sparse open woodland	Trees: *D. lycioides, R. leptodicta*	1

	Grasses: *C. dactylon, P. maximum*	-
Trachypogon spicatus- Bulbostylis burchellii short sparse woodland	Grass: *T. triandra*	1
Aristida junciforms- Arundinella tall closed grassland	Shrub: *Englerophytum magalismontanum*	-
Aristida transvaalensis- Bulbostylis burchellii tall sparse shrubland	-	-
Asparagus krebsianus- Senecio venosus high open shrubland	Tree: *E. magalismontanum*	-
Asparagus virgata- Celtis africana tall closed woodland	Grasses: *T. triandra, P. maximum*	-
Becium obovatum- Protea caffra tall closed woodland	Trees: *Rhus lancea, A. caffra, Z. mucronata*	-
	Shrubs: *L. javanica, Asparagus suaveolens*	-
	Forbs: *H. setosum, Athrixia elata, Vernonia natalensis, Helichrysum nudifolium*	-
	Grasses: *S. sphacelata, T. triandra*	-
Blumea alata- Parinari capensis tall closed woodland	Forbs: *Helichrysum coriaceum, A. elata*	-
	Grasses: *T. biseriata, T. triandra*	-
Brachylaena rotundata- Englerophytum magalismontanum high open shrubland	Trees: *C. molle, E. magalismontanum*	-
	Grasses: *T. biseriata*	
Burkea africana- Setaria sphacelata tall open woodland	-	-
Ceterach cordatum- Tristachya leucotrix tall sparse shrubland	-	-
Cheilanthes viridus- Combretum molle short open woodland	Trees: *C. molle, C. zeyheri*	-
	Forbs: *Solanum panicoides*	
Croton grastissimus- Combretum molle short open woodland	Trees: *C. molle*	-
Cryptolepis oblongifolia- Loudetia simplex tall sparse woodland	Forbs: *Vernonia galpinii*	-
Digitaria eriantha- Lippia javanica tall closed woodland	Trees: *D. rotundifolia, C. zeyheri*	-

Diheteropogon amplectens- Ficinia filiformis short closed woodland	Forbs: *A. elata, Helichrysum coriaceum* Grasses: *T. biseriata, T. triandra*	-
Indigofera comosa- Schizachyrium sanguineum tall closed grassland	Grass: *T. triandra*	-
Loudetia flavida- Tristachys biseriata tall closed shrubland	Shrub: *E. magalismontanum* Grasses: *T. biseriata, T. triandra*	-
Mimussops zeyheri- Hypoetes forskaoli tall forest	Trees: *C. erythrophyllum, R. leptodicta, C. molle, R. pyroides,* Forb: *Solanum rostratum*	-
Ruellia patula- Melinus nerviglumis short open woodland	Trees: *A. caffra, F. saligna* Grasses: *T. biseriata, S. sphacelata, T. triandra*	-
Trachypogon spicatus- Sphenostylis augustifolia tall closed grassland	Grasses: *T. biseriata, T. triandra*	-