ASSESSMENT OF BUSH ENCROACHMENT AND ITS POTENTIAL DRIVERS IN SELECTED LOCATIONS OF THE LIMPOPO PROVINCE, BETWEEN 2001 AND 2018 TIME PERIODS

by

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A DISSERTATION

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DECLARATION

I, Tipanyeka Botsorwane Costa, hereby certify that the dissertation I am submitting to the University of Limpopo for the degree of Master of Science in Geography is original to me, that I did not use it previously for a degree from this or any other university, and that all sources used in it have been properly cited.

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ABSTRACT

The only ecosystem that is best suited to accommodate livestock in Africa is the Savanna ecosystem. The livestock can be raised well in the savanna ecosystem due to the availability of enough grass and trees. However, there has been an expansion in indigenous woody plant species cover, density, and biomass in the savanna ecosystem. Therefore, with an increase in woody cover, also known as bush encroachment; which is globally, threatening grazing resource availability in the Savanna. The study aim was to assess bush encroachment and its potential drivers in selected locations of the Limpopo province, between 2001 and 2018 time periods. The objectives of this study are to highlight areas of bush encroachment using existing remote sensing derived tree cover product over a period between 2001 and 2018 in the Limpopo province; and to determine environmental and socio-economic factors that influence bush encroachment in the Limpopo province. The tree cover change dataset was acquired from the Council of Scientific and Industrial Research (CSIR), and was used to asses bush encroachment. The logistic regression was used to determine which environmental and socio-economic variables influence bush encroachment. When implementing logistic regression to understand drivers of bush encroachment, three scenarios were decided, i) environmental variables only, ii) socioeconomic variables only and iii) environmental and socio-economic data combined. The results of the study show that there has been an increase of bush encroachment over the past years in the Limpopo province. Environmental variables such as temperature minimum, temperature mean and bulk density were found to significantly influence bush encroachment. Similarly, socio-economic variables such as population density and annual income distributions such as household income with no income; income above poverty line; income below average income; average income; and middle average income were found to be significant. Therefore, the study used the applications of remote sensing to assess bush encroachment in the Limpopo province.

Keywords: Savannas, Woody cover, Bush encroachment, Socio-economic, Environmental, Council for Scientific and Industrial Research, Logistic regression, and Remote Sensing

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ROC	The Receiver of Characteristics
AUC	Area Under the Curve
B.E	Bush Encroachment
AIC	Akaike Information Criterion
DRFN	Desert Research Foundation of Namibia
MAWF	Ministry of Agriculture, Water and Forestry
MODIS	Moderate Resolution Imaging Spectrometer
GLM	The Generalized Linear Regression Model
DEM	Digital Elevation Model
JPEG	Joint Photographic Experts Group
CSIR	Council for Scientific and Industrial Research
NRF	National Research Foundation
CO_2	carbon dioxide
RADAR	Radio Detection and Ranging
SAR	Synthetic Aperture Radar

CHAPTER 1

GENERAL INTRODUCTION

1.1. Introduction

Woody and grassy cover coexist in the savanna ecosystem (Bourlière, 1970; Belsky, 1990; Scholes & Walker, 1993; Scholes, 1997; Scholes & Archer, 1997). Savannas are regarded as Africa's most important breeding habitats (Bourlière, 1970; Lamprey, 1983). According to one researcher, 'global research evidence suggests that bush encroachment is deforming savannas' (Archer et al., 1995). The encroachment of woody species on consumable grasses and herbs endangers domestic livestock survival. Furthermore, bush encroachment reduces livestock carrying capacity. The majority of the world's population lives in southern and central African savannas, including a large number of pastoralists whose survival is threatened by bush encroachment (Lamprey, 1983; Scholes, 1997).

Several grazer species suffer when the grassland environment disappears since grass is their primary source of food. The loss of grass cover will reduce the area that can support grazing. The drivers and/or triggers of bush encroachment are believed to be variations in precipitation, atmospheric carbon dioxide, vegetation fires, and land usage (Buitenwerf, Bond, Stevens, Trollope, 2012; Case & Staver, 2017; Aleman, Blarquez, & Staver, 2016; Berry & Kulmatiski, 2017). Over various timelines, all of these components are expected to interact. For example, stochastic fluctuations in rainfall are predicted to provide decadal scale variability, whereas grazing pressure and fire are thought to be the primary drivers of long-term changes in the grass/woody vegetation ratio (Gil-Romera et al., 2010; Scott et al., 1991 & Van Rooyen et al.,2018; Gillson, 2004).

According to some intriguing research, precipitation, fire, and herbivory may all have different effects on the stability of savannas. These factors may also have different effects on invading species (Joubert et al., 2008; Joubert, Smit, & Hoffman, 2012, 2013). As a result, extensive time series with sufficient taxonomic resolution are required to understand stabilizing feedbacks and distinct triggers that result in state shifts. Changing human settlement patterns in response to diseases such as sleeping sickness, a decline in herbivores that browse such as megaherbivores, wildlife, and livestock pandemics such as rinderpest, and intensive harvesting of woody plants for fuel are all notable features of African ecological history (Spinage, 2012). Traditional field surveys have given way to remote sensing technologies such as satellite systems and aerial photography for monitoring bush encroachment (Shantz & Turner, 1958; Madonsela et al., 2017b) (Munyati et al., 2009; Belayneh & Tessema, 2017; Vogel & Strohbach, 2009; Symeonakis et al., 2016; Baumann et al., 2018). New remote sensors are viewed as valuable for monitoring the state of the environment and providing new opportunities as a result of earth observation technology (Ludwig et al., 2016). As a result, remote sensing can identify tangible objects such as soil and vegetation features without coming into contact with them (Hill et al., 2008).

1.2. Problem statement

The impact of bush encroachment decreases grazing carrying capacity of livestock through restraint and replacement of palatable grasses and herbaceous cover (Ward, 2005; Tefera et al., 2007). Therefore, woody species could have resulted into reduced carrying capacity; which led to loss of profit by livestock farmers. Bush encroachment threatens food security and the variety of plant and animal life in the world of between ten and twenty million hectares (Ward, 2005). Supporting evidence brought forward by Chamane (2012), suggests that veldfire, the results of climate change; and the ecological implications are not well comprehended by various communities in the world.

Commercial farmers have suffered significant financial losses as a result of rangeland degradation, particularly in non-migratory ranches in Southern Africa, as well as reduced arable land and animal hunting grounds in African savanna ecosystems (de Klerk, 2004; DRFN, 2009). African countries currently affected by bush encroachment include South Africa, Botswana, Uganda, Zimbabwe, Ethiopia, and Namibia (Ayelew & Mulualem, 2018; Charis et al., 2019). Increasing anthropogenic carbon dioxide led expansion of bush encroachment (Buitenwerf et al., 2012; Kgope et al., 2010); and primary cause of bush encroachment is changes in rainfall patterns. Globally, there are more studies focused on detecting bush encroachment than on monitoring, and the analysis of environmental drivers is even more limited. Therefore, monitoring bush encroachment in the Limpopo province is limited; and this indicates that bush encroachment monitoring and detection is necessary in the province. Remote sensing provides an opportunity to effectively and efficiently monitor vegetation extent, condition and composition. This study evaluates bush encroachment and identifies potential drivers of bush encroachment using tree cover data analysed from remote sensing by Cho and Ramoelo, (2019).

1.3. Motivation of the study

The effect of bush encroachment can cause biome shifts and change savannas to dense vegetation, as well as change the heterogeneity and natural identity of savannas, which is harmful to agricultural productivity and socioeconomic benefits from rangelands (Eldridge et al., 2011). Control management of bush encroaching species using remote sensing technology has the capacity to minimize the burden to keep track of rangeland ecosystems with manuals by range managers. Remote sensing satellites are able to cover wider areas and they are repetitive and less tedious. Conventional field methods are difficult and costly to implement especially in wider landscapes (Provincial to a National scale). Therefore, remote sensing will allow repetitive coverage and effectiveness when collecting field data; and obtaining remotely sensed data is relatively cheaper compared to conventional field sampling methods. Therefore, there is a need to constantly monitor the extent and rate of bush encroachment in the Limpopo province, and determine its potential drivers using remote sensing technology.

1.4. Aims and Objectives

Aim

The aim of the study is to assess the extent of bush encroachment using remote sensing technology and determine its potential drivers in the Limpopo province.

Objectives

The objectives of the study are to:

i. To assess the extent of bush encroachment using existing remote sensing derived tree cover change product over a period between 2001 and 2018 in the Limpopo province.
ii. Determine environmental and socio-economic factors that influence bush encroachment in the Limpopo province.

1.5. Research questions

i. Which areas in the Limpopo province have been affected by bush encroachment between 2001 and 2018 period?

ii. Which environmental and socio-economic factors influence bush encroachment in the Limpopo province?

1.6. Methodology adopted for this study

The Limpopo province has limited control management and monitoring of bush encroachment. Range managers are using manuals to track the impact of bush encroachment on their rangelands rather than using remote sensing technology, which has the potential to reduce the burden of tracking the impact of bush encroachment on rangelands. It is also clear that bush encroachment in the Limpopo province has had a negative impact on agricultural productivity over the years, owing to a lack of sustainable and effective rangeland management. The effect of bush encroachment can cause biome shifts and change savannas to dense vegetation, as well as change savanna heterogeneity and natural identity, which is detrimental to agricultural productivity and socioeconomic benefits from rangelands (Eldridge et al., 2011).

The methodology used to obtain the results for this study was described in details in the study for tree cover conducted by (Cho et al., 2017) and only the first 100 polygons were evaluated for tree cover using the methodology of Cho and Ramoelo, (2019); and the chosen polygons were three-band (red-green-blue) raster image scenes that were saved in Google Earth and later utilized to estimate tree cover change. The Kendall’s Tau coefficient method was used for tree cover change in this study to determine whether or not the area has bush encroachment. Therefore, when analysing the results three groups of variables were selected into environmental variables, socioeconomic variables and a combination of both using ENVI software. The results of this study further show that bush encroachment has been affecting the Limpopo province between the years 2001 and 2018.

CHAPTER 2

LITERATURE REVIEW

2.1. An examination of bush encroachment and its processes

In dry to semi-arid savanna ecosystems, when roughly 40% of arable land and 50% of rangeland land are utilised, bush encroachment is pervasive and expanding quickly (Lukomska et al., 2010; Huang et al., 2018;). Among the African nations affected by bush encroachment are South Africa, Botswana, Uganda, Zimbabwe, Ethiopia, and Namibia (Ayelew & Mulualem, 2018; Charis et al., 2019). According to sources, Namibia is now dealing with a serious bush encroachment problem that is degrading the rangelands (Ayelew & Mulualem, 2018; Schroter et al., 2009). Over 70% of Namibia's territory is made up of arid to semi-dry regions that make up the country's savannas (National Drought Task Force, 1997).

Many academics believe that bush growth is a sign of land degradation (Gibbens et al., 2005; Maestre et al., 2009; Van Auken, 2009). Woody thickening, regrowth, thicketization, thicketization (Kerley et al., 1995; Lechmere-Oertel et al., 2005), woody weed invasion (Booth et al., 1996), and xerification are all terms used to describe encroachment (Van Auken, 2000; Eldridge et al.,2011; Noble, 1997). In South Africa, intensive livestock grazing and subsequent management have resulted in the extinction of desirable grass species in favor of less desirable bushes and shrubs (Hudak, 1999). According to Grossman and Gander (1989), as a result of this, 1.1 million hectares of South African savanna are now inaccessible, another 27 million hectares are threatened, and the area's capacity to graze animals has been reduced.

2.2. The main causes of bush encroachment

2.2.1. Determining the environmental and socio-economic factors that influence bush encroachment.

2.2.1.1. Environmental drivers of bush encroachment

Environmental drivers constitute a global role and purpose of geographic surroundings referred to be extremely beyond management control. These are physical features (e.g., Topography; aspect; soil types and moisture, physical and chemical properties; and vegetation; climatic features; geology); which cannot be managed using technical management strategies. Therefore, in relation to environmental conditions (climatic), moisture is extremely more present in coarse textured, readily available for the plant root uptake (Knoop & Walker, 1985). Therefore, determinants of environmental drivers of bush encroachment are discussed as follows:

i. Fire

Studies identified that savannas are developing into a dense vegetation and evergreen thickets due to lack of fire as a disturbance to bush encroachment, and it has been developing for many years (Gignoux et al., 2009). Therefore, having enough grass loads available, there will be desirable rainfall patterns and effective fire controls to destroy the sapling. In dry areas or semi-arid savanna, where there is a frequent grazing pressure and poor rangeland management; the results will be that dry grass loads for making fuel will not be enough for fire control and management practices. In addition, burning areas of encroachment on the savanna with little grass materials will accelerate the spread and dense of vegetation cover (Van Oudshoorn, 2002).

African authorities prohibit rangeland burning because they do not view fire as a useful tool for managing savanna ecosystems (Dalle et al., 2006). The lack of routine burning, according to ecologists and pastoralists, has facilitated the growth of woody plants (Kgosikoma et al., 2012a). Therefore, controlling fire should be a crucial aspect of savanna administration. Overgrazed savanna ecosystems also have a low fuel load, avoiding frequent, severe fires. Given the significance of fire in savanna ecosystems, it is imperative to create organizations and long-term burning intervals to regulate routine burning in savanna ecosystems (Fatunbi et al., 2008). Alternatively, burning without control can increase the quantity of carbon released into atmosphere and make pastoralists more susceptible to the impacts of drought. It is essential to have knowledge about future climate circumstances as well as the abilities to lessen its negative consequences in order to use fire as a management tool sustainably (e.g., air pollution and carbon loss).

ii. Grazing pressure

Grasses and trees are the most important vegetation type housing in the ecosystem and functions as habitat for other species. Therefore, when savanna grassland component is removed, then trees may increase the effect of bush encroachment. Overgrazing can be caused by livestock and/or wildlife putting high grazing pressure within the rangelands. Overgrazing usually occurs in places where rangeland management strategies are not effectively planned. In essence, overgrazing generally results into a reduced grassland; thus, minimizing carrying capacity and grass load for burning bush. However, in the absence of high grazing oppression, there will be converse effects by supporting production of grass biomass and ultimately cause more frequent fires will be expected (O'Connor et al., 2014).

The majority of rangeland degradation, including bush encroachment, in Africa, according to Moleele & Perkins (1998) and van Vegten (1984), is connected to dense livestock populations around boreholes and kraals. This theory is supported by the observation that along grazing biospheres, plant species density declines as distance from water sources increases. A zone of bush encroachment has been observed between 0 and 300 meters away from foci (boreholes) where there is a significant concentration of grazers or communal grazing grounds in Botswana (Moleele et al., 2002).

Overgrazing may reduce the dominance of grass species, which would then stimulate the establishment and growth of woody species since they would have more access to the soil's moisture (Skarpe, 1990). By dispersing the seeds of encroacher plants, grazing indirectly contributes to bush encroachment. Plants like *Dichrostachys cineria* and *Grewia flava* deposit their seeds with animal faeces near boreholes, where they are later drawn in large numbers due to their high palatability and extensive ingestion by animals. However, some studies have found no link between grazing pressure and bush cover (Oba et al., 2000).

iii. Soil properties

According to Sankaran et al., (2005), the amount of soil clay and tree cover are inversely related. On sandy soil with limited clay component, as the Kalahari sands of Botswana, bush encroachment is more frequent (Kgosikoma et al., 2012b). In the African savannas, woody cover was found to be negatively linked with soil nitrogen, suggesting that increased nitrogen deposition may limit bush encroachment (Sankaran et al., 2008). In a separate investigation, the connection between total soil phosphorus and woody cover was complex and non-linear (Sankaran et al., 2008). Yet, other researchers have found that the soil types in African savannas have no impact on the dynamics of shrubs (Roques et al., 2001).

iv. Rainfall variability

In savanna ecosystems, water scarcity is prevalent, and bush encroachment is associated with variations in interannual rainfall (Angassa & Oba, 2007). With increasing mean annual precipitation in dry and semi-arid regions, the quantity of woody cover and density tends to increase (Sankaran et al., 2005). Locally, a rise in the amount of woody vegetation is encouraged by especially high annual precipitation over a number of years, and invasion species like Acacia mellifera require at least three years of consistently good rainfall to successfully recruit (Jourbert et al., 2008). Woody plant seedlings have an easier time surviving and growing into thickets because grass isn't a major rival and soil moisture is more easily available. According to Rogues et al., (2001) dryness stops bush invasion by restricting plant growth, preventing seed germination, and increasing competition for water at high shrub densities Bush encroachment is a cycle that happens naturally as a result of the development and decline of encroaching plants in reaction to rainfall patterns (Wiegand et al., 2006).

Dryness prevents bush invasion by limiting plant development, inhibiting seed germination, and raising competition for water at high shrub densities, according to Rogues et al., (2001). Due to the growth and decline of encroaching plants in response to rainfall patterns, bush encroachment is a cycle that occurs naturally (Wiegand et al., 2006).

v. Climate change

High atmospheric CO_2 concentrations may have an impact on savannas and contribute to bush encroachment, according to Smit (1999), Wigley et al., (2009), Ward (2010), and (Buitenwerf et al., 2012). The introduction and implementation of the Industrial Revolution have increased CO_2 concentrations in 2014 (397 parts per million) and have reached 397 parts per million in 2014; and that CO_2 uprising is expected to be 450 ppm prior 2030 (Cha et al., 2017). The increasing CO_2 concentrations in the atmosphere may lead to global warming; and may also put an imposing direct threat and impacts on ecosystem functioning and its structure; and plant physiology and productivity (Ceulemans,1999). Furthermore, semiarid savanna ecosystems with limited water, and sometimes experience no rainfall at all, having a subsequent effect on bush encroachment and variability in annual rainfall (Angassa & Oba, 2007). Therefore, during dry seasons when there is a limited plant growth and productivity which can cause death to other plant species (Roques et al., 2001); therefore, in several cases minimize the risk and spread of bush encroachment.

2.2.1.2. Socio-economic drivers of bush encroachment

In the context of this study, socioeconomic concerns are those that have a negative impact on a community's economic activities, such as a lack of education, prejudice based on culture and religion, overcrowding, unemployment, and poverty. The latter frequently establishes socioeconomic status, or a person's or a group's place in a hierarchical social structure, which is defined by a combination of factors such as employment, education, income, wealth, and place of residence (Erreygers, 2013). As the population grows, so do basic needs, and so do the incentives for cattle production. As a result, the availability of grasses has decreased, allowing trees to dominate, resulting in bush encroachment. The process of urbanisation implies that areas in rural villages must be abandoned, which supports bush encroachment by reducing wood harvesting, timber, and fire frequency. Distance from the road to the forest, where road access is restricted and poor forest management is experienced, usually encourages bush encroachment in savanna ecosystems, threatening grass cover survival.

2.2.2. Unsustainable land-use management

In dry land environments, unsustainable land use practices like expanding rain fed farming over unsuitable lands, soil mining, cutting down on fallow periods, overgrazing, and unrestricted biomass gathering are major causes of bush encroachment (De Beer et al., 2005). If livestock numbers are not effectively monitored, grass may be lost, leading to bush encroachment and unsustainable land-use management. Land degradation, on the other hand, is largely the result of unsustainable rangeland management systems (Tainton, 1999). The main drawbacks of a shared livestock system are the difficulties in managing rangeland resources, which are the result of multiple resource partnerships (Sive, 2016). As a result, in this practice, all joint groups have equal access and authority to management and can carry out their own production activities (Mapekula, 2009). Multi-ownership complicates decision-making for communal farmers and makes rangeland management strategies difficult (Hardin, 1968). As a result, as the population grows, so does the demand for ecosystem resources and services.

2.3. Impact of bush encroachment

i. Loss of grazing resources

Agriculture productivity has been significantly impacted economically by Bush encroachment, leading to a major gap in production failure. Due to the effects of bush encroachment, there is a low amount of livestock output (de Klerk, 2004). Furthermore, some animals generated less due to the encroachment of the bush (Kruger, 2002). The impacts of grazing may be reversed by reducing animal grazing pressure; as a result, management goals should be to establish a long-term carrying capacity between grazing pressure and successional tendency (Ellis & Swift, 1988; Westoby et al., 1989).

ii. Creating new habitat for birds

A large scale of bush dominance in savanna ecosystems can result in a significant and systematic change in habitat diversity (Ward, 2002; 2005, Wiegand et al., 2005; 2006). Due to changes in habitat structural variety brought on by bush encroachment, the diversity of bird species is declining, posing a threat to their existence. If grasslands and other food sources for herbivores are not removed, bush encroachment may have a beneficial effect on land production (Ward, 2005; Kraaij & Ward, 2006; Wigley et al., 2009). Due to habitat destruction, the endemic cape vulture of Southern Africa, for instance, is now extinct and no longer breeds in Namibia. As a result, the cape vulture bird requires long flat areas to run and take off flying high in the air, making it more difficult for them to cope with bush encroachment (Welz, 2013).

iii. Impact on botanical diversity

Bush encroachment threatens botanical diversity and it has been indicated that woody vegetation overtakes plants species (de Klerk, 2004). Trees that always encroach much can dislocate and remove other species availability and eventually resulting to the removal of other plant species. Encroaching woody cover have an outward and a well-developed taproot that goes down deep into the soil to get moisture and nutrients for growth and development (Walker et al., 1981). In addition to this, grass roots system normally appears in the topsoil layer; and have not been able to get deep down into the soil layers (de Klerk, 2004).

iv. Impact on mammalian diversity

Animals that prefer densely vegetated areas are hampered by the density of tree species. A lack of accessible browsers in the trees cover will eventually lead to an increase in bush encroachment. Subsequently, sixteen other mammalian species like to dwell within an opened woodland area as habitat (Joubert, 2003). Therefore, the increase in vegetation cover can have major disturbances in conservation areas, monitoring and management, especially looking at the savanna ecosystem (Tews & Jeltsch, 2004). Therefore, trees that have greater volume of encroachment will negatively influence areas that require unlocked savannas as their habitat. Dense vegetation prohibits mobility of browsers, and at the same time threatens their survival and freedom; thus, affecting their hunting habit and foraging success.

v. Impacts with specific to the groundwater

Water is the most important factor influencing bush encroachment. Water is critical in every way, given the country's aridity and the effects of climate change. The encroachment is estimated to have lost approximately 12 million M3 of water through transpiration over a 10 000ha area (NAU, 2010). Encroachment currently affects 33% of the 476 548 K2 of low groundwater potential, 52% of the 323 333 K2 of intermediate groundwater potential, and 89% of the 24 247 K2 of high groundwater potential (NAU, 2010). Almost 80% of Namibia is dependent on groundwater, which is the country's most important source of water during dry spells (NAU, 2010; UNFCCC, 2010). Although S. mellifera species transpires at least six times more than other bushes and shrubs, necessitating approximately 2000 litres of water in 8 hours per day, the situation may be worse (Larcher, 1983 & Donalson, 1969; NAU, 2010). The species has a deep root system that extends over 30m and has an effect on the water table at farm Aiams in the Otavi district (NAU, 2010). Boreholes dug by farmers in the Platveld aquifer area were initially 7m deep in 1940, but had dropped to an average depth of 85m by 1990. In order to ensure that there would always be enough water, the number of boreholes was raised.

vi. Socio-economic impact of bush encroachment

Invasion of woody cover to the savanna has a negative influence on the socioeconomic lifestyle especially in rural areas, and the impact that it has can affect farmers who use the land for different activities. According to the perspectives and analysis of this study, socio-economic variables are population densities, education, employment and income household. However, in other studies, the impact of bush cover on ecosystem services and functions was primarily focused on biological processes and economic interference, with little attention paid to land users' perspectives and impact management (Eldridge et al., 2011, Anadon et al., 2014). As a result, this explains why most involvements fail because their system ignores land users' participation (Menzel & Teng, 2010; Mcnally et al., 2016).

2.4. Management of bush encroachment

There are many methods implemented to control and reduce the impact of bush encroachment in the rangelands, and these methods are called bush encroachment management systems (Fulbright, 1996). Subsequently, these control methods have varying policy implication for bush control (Olson & Whitson, 2002). Therefore, applying knowledge and understanding must be the potential roles played by various techniques and methods employed for bush encroachment controls, and to promote grass layer composition which requires acknowledgement of the objectives of resource users, and policy makers for decision-making. Therefore, management methods of bush encroachment which are discussed are globally recognised as possible mitigation measures to monitor bush encroachment in South Africa (Barac, 2003).

2.4.1. Mechanical control

This control method is simply in the form of clearing trees, and which is the costliest method to perform; and it is usually utilized as additional to various methods of monitoring and measurements. Therefore, this system starts from tree cutting by using physical strength to stumping by using tractors and bulldozers. However, the method of monitoring and controlling bush encroachment in mechanical control is extremely costly and labour intensive; and it also have a restricted role in most areas where problems are mostly encountered (Hoffman & Todd, 1999). However, the mechanical cutting method has disadvantages and one of them is of suppressing thickening and development of trees within a short-term period and later vegetation regrows back to woody cover (Clark & Wilson, 2001).

2.4.2. Chemical control

The chemical method of woody species using chemical substances is usually carried out extensively on a large-scale analysis; and produces immediate better results when used appropriately, i.e., sprayed aerially. As a result, in 1980, at bush encroachment workshop seminars, precautions for chemical application methods were introduced. Some of the chemicals used and recommended include Hyvar X, Tordon 225, Tordon Super, Garlon, Ustilan, Graslan, Grazer, and Reclaim (Hoffman & Todd,1998). In general, the size of the target area to be applied, available financial support, and professionally well-trained labor are all factors to consider (De Klerk, 2004). Furthermore, Tebuthiuron (C9H16N4OS) is a potent and dynamic ingredient found in many arborocides used to reduce the impact of bush encroachment.

2.4.3. Biological control

Mechanism of controlling bush encroachment in this method usually involves the role of browsers and fire. Therefore, Goats and other domestic animals can be used appropriately to browse trees and shrubs. Furthermore, browse animals will succeed in lowering impact of bush encroachment and allow access for cattle farming to get in underneath the trees. Goats in this system are used to minimize trees from growing up and keeping invading trees short. It is imperative to establish breeding system for browse and domestic animals to control bush encroachment. However, this idea has been ignored and have not been carefully explored; and this calls for effective training and practical work.

2.5. Integrated approach is needed to understand causes of bush encroachment

A multidisciplinary strategy that incorporates ecological and indigenous ecological knowledge is necessary to comprehend the causes of bush invasion (Sop &

Oldeland, 2011). Additionally, this approach ensures that issue solutions are ethical from an economic, cultural, and environmental standpoint given the local circumstances. Indigenous ecological knowledge gathered through extensive land use and observation in Africa, where there are few long-term ecological data, could complement scientific knowledge by offering a long-term view on vegetation change and underlying causes (Bart, 2006). Therefore, these studies do not take into consideration the confounding effects of other variables and simple models that concentrate on a single variable are unlikely to explain the causes of bush encroachment.

According to Van Auken (2009), it is very likely that the bush invasion factors mentioned above will combine to encourage the development and dominance of bushy vegetation. A multidisciplinary strategy that incorporates ecological and indigenous ecological knowledge is necessary to comprehend the causes of bush invasion (Sop & Oldeland, 2011). Furthermore, given the regional circumstances, this strategy ensures that problem solutions are economically, culturally, and environmentally sound. Due to a mere concentration on technology and a disregard for socioeconomic concerns, the majority of rangeland development programs have been unsuccessful (Squires et al., 1992).

In order to ensure that a common goal is established and that any strategies (or regulations) employed to minimize bush encroachment take into consideration the way of life of that specific community, it is helpful to use both traditional and scientific ecological knowledge. Modern grazing regulations must promote open, flexible decision-making that considers a broad range of information and values. Bush encroachment management must put a heavy emphasis on managing grazing pressure and choosing the right burning intervals because variables like rainfall and soil quality cannot be managed.

2.6. Assessment and monitoring of bush encroachment

2.6.1. Conventional assessment of bush encroachment

The forces driving bush encroachment are not fully understood, and this has resulted in a lack of proper and effective forestry management (Ward, 2005). Remote sensing had achieved quantitative rigour or thoroughness in analyzing the global impact of bush encroachment (Rohde & Hoffman, 2012). As a result, traditional data collection methods such as lateral photographs and aerial photographs are time consuming and labor intensive, and are more difficult and costly to implement, particularly in larger landscapes (Provincial to a National scale). Although these traditional methods provide recorded information about landscape levels of change and can capture an overview spectrum of the ecological sphere of life through repeated photography on bush invasion, they are more complex and costly to implement, particularly in the case of bush invasion.

2.6.2. Remote sensing assessment of bush encroachment

2.6.2.1. Mapping areas of bush encroachment using existing remote sensing derived tree cover product

Several investigations have discovered errors in the categorisation of woodlands in Southern Africa's current global forest cover maps (Sedano et al., 2005; Gong et al., 2013; Fritz et al., 2010). Hansen et al., (2000), Loveland et al., (2000), Friedl et al., (2002), and Tateishi et al., (2011) are a few authors who have contributed to this work. For instance, Sedano et al., (2005) concluded that global land cover products lack the detail evidence necessary for resource management at the national and provincial levels after finding more than 50% errors in the Moderate Resolution Imaging spectrometer MODIS - MOD12Q1 land cover product in the Miombo woodlands of Mozambique. A systematic bias in tree cover prediction was found by Sexton et al., (2013), and it shows up as overprediction in sparsely forested areas.

2.7. Statistical Models used for understanding the interactions and relationships between environmental and socio-economic variables

2.7.1. Generalized linear regression models

McCullagh and Nelder (1972) extended Nelder and Wedderburn's generalized linear regression model (GLM). The GLM has two key framework enhancements in addition to the fundamental structure of linear regression equations. A form that is linearly linked to the predictors is created from the predicted value in order to handle nonlinear predictor-criterion connections; a link function then links the predicted and observed criterion scores. Second, the GLM takes error structures besides the linear regression's normally distributed error structure (i.e., conditional distributions of outcome variance). The generalized linear model is made up of the systematic component, the random component, and the link function. The model for the expected value is connected to the ordinal logistic regression's systematic component. It describes how the model's independent variables, which are all functions of the predicted value of Y, interact with one another.

2.7.2. Statistical analysis: Logistic regression

The logistic regression method is commonly used to study two independent variables and a categorical dependent variable. Logistic regression can also be used to calculate the likelihood of an occurrence by feeding data into a logistic curve. The two kinds of logistic regression models are multinomial logistic regression and binary logistic regression. When the dependent variable is dichotomous and the independent variables are either continuous or categorical, binary logistic regression is commonly used. A multinomial logistic regression can be used if the dependent variable has more than two groups and is not binary. Many of the key assumptions of linear regression models based on ordinary data are not required in logistic regression. Stepwise regression is also a backward and forward elimination method. When variables are introduced or removed early in the process and we subsequently decide to change our thoughts, this is helpful.

2.8. Environmental variables

A map of slope, aspect or relief, and curvatures, for example, can be used to spatially resolve all DEM (digital elevation model) derived maps. Because of grazing-induced reductions in the herbaceous layer and limited fire frequencies, the increase in vegetation cover would have been much larger (Archer, 1995). As a result of abandoned lands that lack proper rangeland management and monitoring, woody coverage has replaced the yield of the grass layer in the Borana lowlands. As a result, there are now fewer large grazing areas for livestock feeding and, eventually, become a home for dangerous animals, preventing access to the grass biomass that is currently available (Gemedo et al., 2006a).

2.9. Socio-economic variables

A savannah ecosystem has become dysfunctional due to bush encroachment, in which trees outcompete grasses in open savannas by growing quickly, causing grassland to disappear. To be more resilient in general, closer involvement in forest management and control of dense woody species is required (O'Connor et al., 2014).

As a result, distance from the road and built-up areas indicates that sites with greater distance from roads and built-up areas have higher ecosystem multifunctionality. The greater the distance from roads and developed areas, the greater the density of woody species. An ecosystem that is inaccessible for movement is difficult to monitor and manage, and this type of ecosystem structure will eventually result in bush encroachment. Population density, employment, education, and household income are the socioeconomic variables examined in this study. Thorn trees cover an estimated 10-12 million ha, or 12-14% of the land, according to Feller et al., (2006), causing some animals to migrate to less hospitable areas. He asserted that a 700 million dollar loss in yearly economic output had a direct detrimental effect on the socioeconomic activities of 65,000 communal households and 6,283 commercial farmers and their staff.

2.10. Conclusion

Remote sensing has been established as an essential tool for understanding potential drivers of bush encroachment and its spread, as well as monitoring and assessment. Furthermore, many studies concentrate on bush coverage analysis rather than monitoring. Overgrazing, uncontrolled fire and drought, seasonal changes in rainfall, and climate change are the driving forces behind this phenomenon. To diagnose, prevent, control, and manage the impact of bush encroachment, integrated plant invasion management methodology has been introduced. The diagnostic stage entails identifying and characterizing the invasion; the control stage entails integrating the invasion and approaching strategies. Finally, mechanical, chemical, biological, and manual treatment should be included in the management strategies.

CHAPTER 3

METHODOLOGY AND ANALYTICAL PROCEDURES

3.1. Study area

The study was conducted in the Limpopo province. The map in Figure 1 depicts the Limpopo province, which includes five district municipalities. Limpopo province has hot weather, with an average temperature of 27 degrees Celsius. The weather in the lowveld is hot, with an average temperature of 45 degrees Celsius. The Limpopo River Basin's annual rainfall ranges from 200 mm in hot dry areas to 1 600 mm in high rainfall areas. The main Limpopo River Valley contains the majority of the hot and dry areas that receive 200 mm to 400 mm of annual rainfall. The Limpopo River basin's dominant biomes are tropical and subtropical grasslands, savannas, and shrublands. Limpopo province is known for its fertile soil and abundant rainfall.

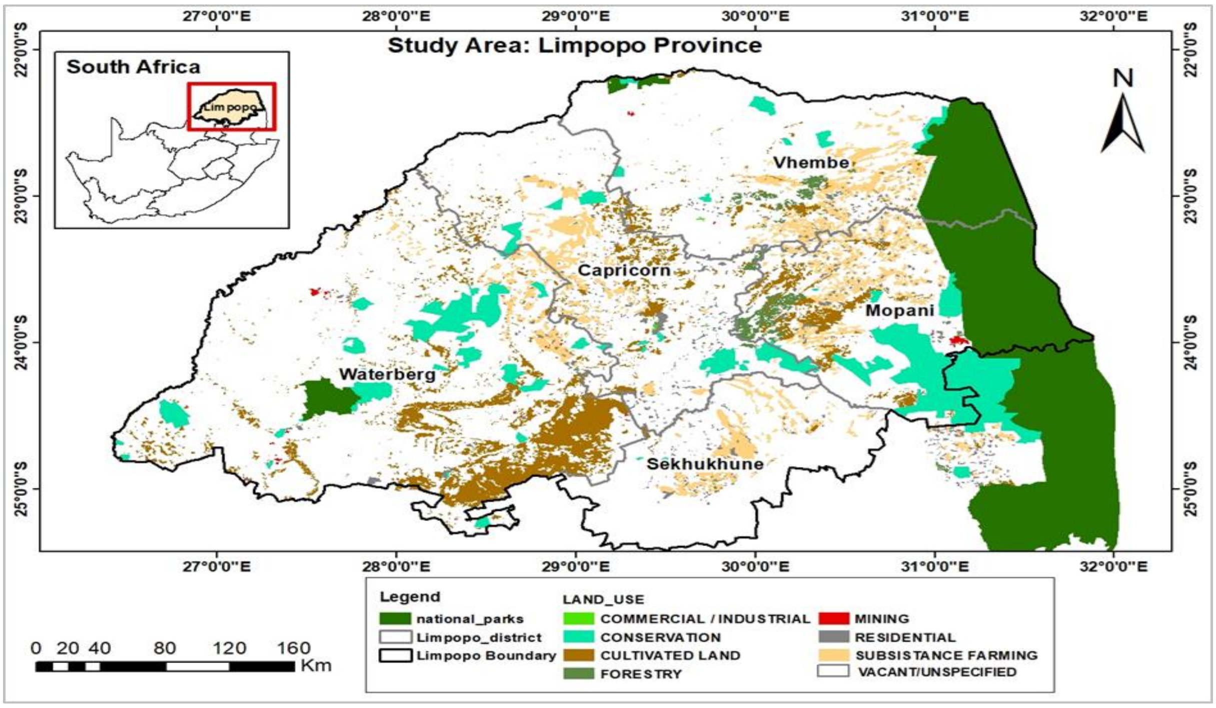

Fig 3.1. The study area, which includes the five district municipalities of the Limpopo province as well as various land cover features (2020). (Source: egis.environment.gov.za, Department of Environmental Affairs).

3.2. Tree cover data

The method used in this study to calculate the percentage of trees was described in detail by (Cho et al., 2017). On the MODIS image scene, 150 arbitrary 4 by 4 pixel or 1000 m by 1000 m polygons were created, translated to keyhole markup language file format, and superimposed on a high-resolution Google Earth image using the Google Earth software (Google Inc). As a result, the investigation was limited to polygons that did not change in tree cover between 2001 and 2018. The first 100 polygons were evaluated for tree cover using the methodology by Cho and Ramoelo, (2019), and the chosen polygons were three-band (red-green-blue) raster image scenes saved in Google Earth and then used to estimate the change in tree cover. The chosen polygons were two-groups of three-band (red-green-blue) raster picture scenes that were initially imported into ENVI software after being stored in Google Earth.

The sites were chosen based on the existing tree cover layer, with a particular emphasis on areas with significant increases in vegetation cover (Cho & Ramoelo, 2019). The existing tree cover datasets between 2001 and 2018 periods were used to create the woody canopy cover. In the research, only polygons with constant tree cover from 2001 to the present (typically 2016–2018) were employed. This was achieved by examining old pictures of each hexagon. Settlements, plantation forests, and agricultural land were not included in the research. Additionally, only pictures captured from November to April during the summer months were used because the savanna's tree canopy cover changes with the seasons.

The degree of deviation from nutrition and fluid guidelines, for example, are two variables that are assessed using this method as paired observations for each patient in the sample. Calculating the correlation between the two variables is feasible if at least one of the variables is ordinal. Like Spearman's rank correlation, Kendall's tau is applied to data ranks analysis (Crichton, 1999). Simply put, each variable's values are ordered from lowest to highest, with 1 denoting the lowest value, 2 the next lowest, and so on. Conover, (1980) explains how to compute Kendall's tau. A positive correlation means that the ranks of both variables rise together, and a negative correlation means that as one variable's rank rises, the rank of the other variable declines. Kendall's tau, like other measures of correlation, will accept values between 1 and +1.

According to the study of structural categories of vegetation, trees 0.5 to 3 m tall covering more than 25% of the ground indicated the presence of bush encroachment, while trees 0.5 to 3 m tall covering less than 25% indicated the absence of bush encroachment (Pratt et al.,1966). As a result, the study used the method modified from Pratt et al., (1996), whereby structural categories of vegetation associated with values greater than 0.5 to 3 m were indicating presence of bush encroachment, whereas values less than 0.5 to 3 m were not associated with woody cover, indicating the absence of bush encroachment.

Table 1 contains a list of environmental and socioeconomic data to be tested as drivers of bush encroachment, as well as their respective sources. The majority of the environmental and socioeconomic data in Table 1 are freely and easily accessible.

Table 1: The Environmental and Socio-economic data

Environmental	**Variables**	**Type**	**Resolution**	**Source**
	Elevation	Continuous	30 M	DEM, https://dwtkns.com/srtm30m/
	Precipitation	Continuous	1 KM	www.chelsea.co.uk
	Temperature Maximum	Continuous	1 KM	www.chelsea.co.uk
	Temperature Minimum	Continuous	1 KM	www.chelsea.co.uk
	Temperature Mean	Continuous	1 KM	www.chelsea.co.uk
	Sand	Categorial	30 M	SOTER Database (https://www.isric.org/explore/soter) or soilgrids website (https://soilgrids.org/).

	Clay content	Categorial	30 M	SOTER Database (https://www.isric.org/explore/soter) or soilgrids website (https://soilgrids.org/).
	Soil organic content	Categorial	30 M	SOTER Database (https://www.isric.org/explore/soter) or soilgrids website (https://soilgrids.org/).
	Nitrogen	Categorial	30 M	SOTER Database (https://www.isric.org/explore/soter) or soilgrids website (https://soilgrids.org/).
	Bulk density	Categorial	30 M	SOTER Database (https://www.isric.org/explore/soter) or soilgrids website (https://soilgrids.org/).
	Woody cover	Categorial	250 m	www.csir.gov.za
	Livestock per unit hectare	Continuous	90 m	www.ldard.gov.za
Socioeconomic	Population density	Categorial	$KKmm^2$	www.statssa.gov.za
	Employment	Categorial	$KKmm^2$	www.statssa.gov.za
	Income distributions	Categorial	$KKmm^2$	www.statssa.gov.za
	Education	Categorial	$KKmm^2$	www.statssa.gov.za

3.3. Statistical data analysis

The logistic regression analysis was used to determine which environmental and socioeconomic factors influence bush encroachment and was implemented in stepwise. As a result, the logistic regression model employed three modelling scenarios: environmental variables only, socioeconomic variables only, and a combination of the two. The environmental and socioeconomic variables were combined to determine the drivers of bush encroachment. When selecting significant environmental and socio-economic variables, the ArcGIS software 10.4.1 and Envi 5.3 were used to extract the values of various environmental and socioeconomic variables, and prepare data for analysis. Stepwise logistic regression was used in each scenario, and the combination of variables with the lower Akaike Information Criterion (AIC) threshold were chosen. The variables that were optimal based on the AIC when running a stepwise variable selection using the AIC were used to build the logistic regression model. The overall statistical analysis was completed with a 95% confidence interval ($p<0.05$).

3.4. Model validation

The importance of accuracy assessment is to determine the quality of the evidence obtained from remotely sensed data. The accuracy assessments are both qualitative and quantitative. Qualitative assessment methods are very quick and used to test whether the remote sensed data or map looks right; and test if they correspond to what is on the ground. Quantitative assessment methods are used to identify and quantify errors, e.g., bias and root mean square errors. Remote sensed data are often used for mapping and developing environmental models that are used for control management and decision-making purposes.

Data splitting is a method of dividing accessible data into two sections that is frequently used for cross-validation. A prediction model is built using the first collection of data, and its performance is evaluated using the second set. As a result, we used sixty percent (60%) of the data for training and the remaining forty percent (40%) for validation. Logistic regression model was used to determine which environmental and socioeconomic factors influence bush encroachment, and stepwise regression was implemented to run all the variables within the model. As a result, the model included environmental variables only, socioeconomic variables only, and a combination of both. All variables were validated using the same method of data splitting.

For the purpose of evaluating the precision of projected trends in tree cover, high-definition Google Earth images were used (Cho et al., 2017). Both tree recruitment and the expansion of current tree canopies can result in significant rises in tree cover (i.e., increasing leaf area index). While the gradual thinning of the forest caused by activities like wood harvesting, elephant tree felling, or bush fires may result in a discernible decrease in tree cover. Due to the greater prevalence of this phenomenon than the decreasing trend, we only carefully assessed the accuracy of polygons that were mapped as having a significant rising trend in tree cover. Evidence-containing polygons were assigned the numbers one (1) and zero (0).

The validation of this study was carried out between 2001 and 2018, when the aerial imagery was gathered. The MODIS image scene was used to generate 150 randomly chosen 4 by 4 pixel or 1000 m by 1000 m polygons, which were then converted to keyhole markup language file format and overlay on a high-resolution Google Earth image using the Google Earth program. This was done to make sure that each class' evaluation would include a sufficient number of samples (Google Inc). Estimates were made for total classification accuracy, contingency matrices, omission and commission errors, and overall kappa indices (Cohen, 1960).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Results

Environmental variables such as minimum temperature, mean temperature, and bulk density significantly explain the variability of bush encroachment; and socioeconomic variables such as population density, education, employment, and income distributions were also significant in explaining bush encroachment in the Limpopo province. Fig. 4.1, shows the environmental and socio-economic factors that influence bush encroachment in the selected locations of the Limpopo province. Fig. 4.2, shows the tree cover change map showing the extent or degree of bush encroachment and the hotspot areas using the Kendall's Tau coefficient, in the selected locations of the Limpopo province between 2001 and 2018 periods.

4.2. Tree cover and bush encroachment hotspots based on the existing tree cover data in the Limpopo province.

4.2.1. Tree cover change using NDVI and time series analysis (Cho & Ramoelo et al., 2019).

4.2.1.1. Bush encroachment in the Vhembe district municipality

According to the analysis of Cho and Ramoelo, (2019) of tree cover change data, Thulamela, Collins Chabane, Makhado, and Musina local municipality were the hotspot areas of bush encroachment in the Vhembe district, with a confidence level of 90-99% and 95-99% at Thulamela, indicating a moderate to high presence of tree cover change; whereas cold spot areas have a confidence level of 90-99%, indicating a low presence of tree cover The changes in tree cover in the Vhembe district ranged from -0.05 to -0.93 m height, 0.05 to 0.5 m height, and 0.5 to 0.93 m height. Specific environmental and socioeconomic parameters were significant within the four local municipalities while others were not because, using the Akaike Information Criterion (AIC), the variables that were significant to the study were those related to woody cover. The results of this study further demonstrate that between 2001 and 2018, there was no influence of bush encroachment in Collins Chabane local municipality.

In the Vhembe district municipality, bush encroachment was correlated with population density, education, yearly income levels, minimum and mean temperatures, and low to medium bulk densities. Long-term ecological data and indigenous ecological knowledge gathered through long-term observation and land use are in conflict in the setting of Africa. By offering a long-term view on changes in forest cover and their underlying causes, indigenous ecological knowledge could complement scientific understanding (Allsopp et al., 2007; Bart, 2006).

4.2.1.2. Bush encroachment in the Mopani district municipality

Tree cover change in the Mopani district municipality ranges from -0.05 to -0.93 m height; from 0.05 to 0.5 m height; and from 0.5 to 0.93 m height. Ba-Phalaborwa, Greater Letaba, Greater Tzaneen, and Maruleng local municipalities were the areas of hotspot in bush encroachment for Mopani district, with a confidence level of 90-99%; and Greater Letaba and Greater Tzaneen local municipalities had a confidence level of 90-99% of cold spot areas of bush encroachment. According to the Akaike Information Criterion (AIC), the variables that were significant to the study were those related to woody cover with a p-value less than 0.05 and predictor variables were correlating to bush encroachment. Bush encroachment was correlated with population density, yearly household income levels, and low to medium bulk density within these local municipalities located in the Mopani district. Relationships between soil clay concentration and bulk density and tree cover are adverse (Sankaran et al., 2005). Therefore, soil clay content and bulk density were tested and found not to be correlated to bush encroachment for this study.

4.2.1.3. Bush encroachment in the Capricorn district municipality

Capricorn district is the second largest affected by bush encroachment in the Limpopo province. According to Cho and Ramoelo (2019) analysis of tree cover change, the local municipalities most affected by bush encroachment were Blouberg, Lepelle Nkumpi, Molemole, and Polokwane. The tree cover change in the Capricorn district municipality ranges from -0.05 to -0.93 m height, 0.05 to 0.5 m height, and 0.5 to 0.93 m height. In the district, four local municipalities have hotspots of bush encroachment with a confidence level of 90-99%, and two have cold spot areas with a confidence level of 90-99% in Lepelle Nkumpi and Polokwane. The Capricorn district municipality's tree cover change extends from the Waterberg district to the Mopani district and Vhembe district municipalities.

According to the Akaike Information Criterion (AIC), the variables that were significant to the study were those related to woody cover with a p-value less than 0.05 and predictor variables were correlating to bush encroachment. Selected environmental (low to medium bulk density, minimum and mean temperature) and socioeconomic (population density, education, and income distributions) were the variables linking the bordering district municipalities in bush encroachment.

4.2.1.4. Bush encroachment in the Sekhukhune district municipality

The study shows that Sekhukhune district had very little bush encroachment between 2001 and 2018 periods. Ephraim Mogale local municipality was the area of hotspot with confidence level of 90% tree cover change, while other areas of cold spot having a confidence level of 90-99% tree cover change. Tree cover change in the district municipality ranges from -0.05 to -0.93 m in height, 0.05 to 0.5 m in height, and 0.5 to 0.93 m in height. According to the Akaike Information Criterion (AIC), the variables that were significant to the study were those related to woody cover with a p-value less than 0.05 and predictor variables were correlating to bush encroachment. The study discovered that socio-economic variables such as population density, education, and income distributions, as well as medium bulk density and temperature minimum and mean, were significant to the study. Additionally, research has shown that the amount of bush cover and grazing pressure are not substantially related (Oba et al., 2000). Therefore, the grazing carrying capacity was not determined to be contributing bush encroachment in this study.

4.2.1.5. Bush encroachment in the Waterberg district municipality

The Waterberg district municipality was found to be the area of hotspot in bush encroachment in the Limpopo province and the areas of hotspot were Bela-bela, Modimolle-Mookgophong, and Thabazimbi local municipalities, with a confidence level of 90-99%, and cold spot areas having a confidence level of 90-99% tree cover. The findings of this study, as shown in fig 4, indicates that there was no impact of bush encroachment in the Mogalakwena local municipality between 2001 and 2018.

In the Waterberg district municipality, tree cover change ranges from -0.05 to -0.93 m in height; from 0.05 to 0.5 m in height; and from 0.5 to 0.93 m in height. According to the Akaike Information Criterion (AIC), the variables that were significant to the study were those related to woody cover with a p-value less than 0.05 and predictor variables were correlating to bush encroachment. Some of the local municipalities, such as Lephalale and Mogalakwena, did not experience the impact of bush encroachment between 2001 and 2018 periods due to stabilized changing temperature minimum and mean, population density, and low to medium bulk density. Therefore, Fig 4.1 and Fig 4.2 below show the tree cover change and bush encroachment hotspot areas in the Limpopo province between 2001 and 2018 periods.

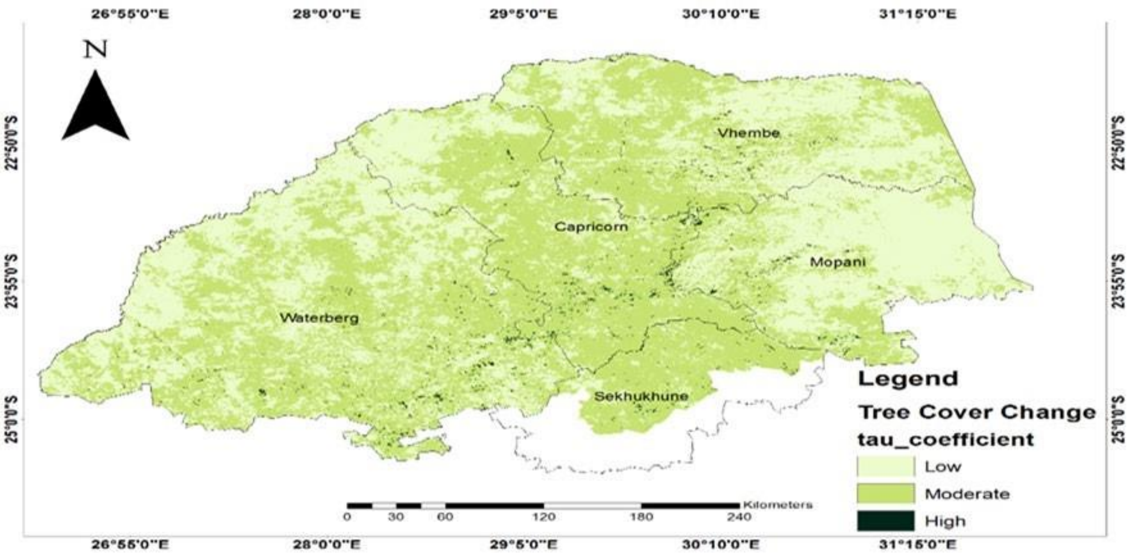

Fig.4.1. Tree cover change map, showing the extent of bush encroachment and the hotspot areas using the Kendall's Tau coefficient, in the selected locations of the Limpopo province between 2001 and 2018 periods.

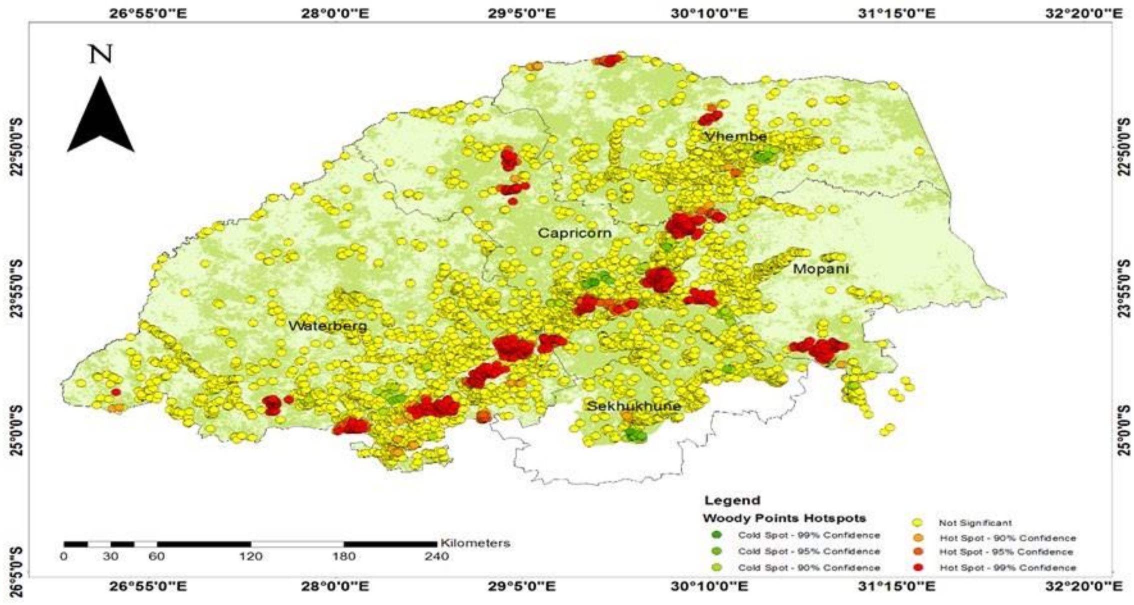

Fig.4.2. Areas of hotspot map, showing how environmental and socio-economic factors that influence bush encroachment are distributed in the selected locations of Limpopo the province between 2001 and 2018 periods.

4.3. Environmental variables as drivers of bush encroachment

Table 2: Significant environmental variables as drivers of bush encroachment

Environmental Variables	P-Value	Estimates
Temperature Minimum	0.00112	-6.40716
Temperature Mean	0.00038	5.63979
Bulk density	0.01985	0.04401

The logistic regression model's goodness of fit was 0 and its p-value was less than 0.05, indicating that the model is statistically significant for analysing bush encroachment-related drivers. There were 6228 degrees of freedom in the model, and the correlation co-efficient was 0.9893369. The bulk density co-efficient estimations were equal to zero, and the result of 0.5 showed a substantial association for bush invasion. Indicating a higher positive connection for bush encroachment, the coefficient estimates for temperature mean were greater than 0.5, while those for temperature minimum were less than 0.5, indicating a low correlation for bush encroachment. In the study, model performance was also assessed using the ROC (Receiver Operator Characteristic) and AUC (Area Under the Curve) curves, binary classification issue evaluation metrics. The regression model's AUC of 0.9996, which corresponds to the scenario above, shows that the classifier functioned brilliantly.

It was necessary to convert the response variable in the number structure to a factor because it has two factors, 0 for non-woody cover and 1 for woody cover. A misclassification error of 0.0008 was found while using the training dataset, indicating woody cover, whereas a misclassification error of 0.002 was found when using nonwoody cover. As a result, the actual misclassification error for woody cover testing data was 367 and 561 for training data. The study's model summary was then put to the test to determine which predictor factors were statistically significant. With a confidence level of 0.95 p-value, the asterisk in the model summary indicated which variables were significant. Fig. 4.3 below, shows the ROC (The Receiver Operator Characteristic) and AUC (The Area Under the Curve) of logistic regression model for environmental variables.

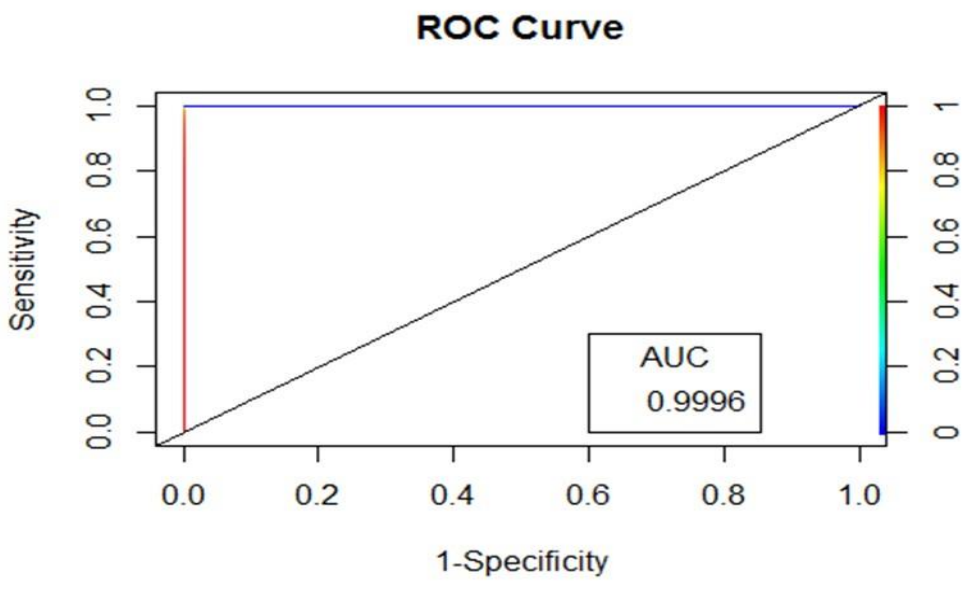

Fig. 4.3. ROC (The Receiver Operator Characteristic) and AUC (The Area Under the Curve) of logistic regression model.

4.4. Socio-economic variables as drivers of bush encroachment

Table 3: Significant socio-economic variables as drivers of bush encroachment

Socio-economic variables	P-Value	Estimation

Population density	0.000152	-0.17
AHH income_ No income	0.035134	-0.13
AHH income_ Income above poverty line	<0.05	0.08
AHH income_ below average income	0.018536	-0.00
AHH average income	0.028994	-0.01
AHH middle average income	0.006313	-0.04

When analysing the factors that influence bush invasion, the logistic regression model's goodness of fit was 1.438355e-195 and its p-value was less than 0.05, showing that the model is statistically significant. Indicating a low association for bush encroachment, the co-efficient estimates for population density, yearly household income and no income, annual household income below average income, and annual household income and middle average were all less than 0.5. A substantial correlation exists between bush encroachment and the co-efficient estimates for annual household income over the poverty line, which were equal to zero and had an outcome of 0.5. The correlation co-efficient of the model was 0. 2454576 and it has 6228 degrees of freedom. The study used the ROC and AUC evaluation measures for binary classification issues to assess model performance further.

It is a probability curve that effectively separates the TPR from the FPR at various threshold values. AUC is used to summarize the ROC curve and is a measure of a classifier's ability to distinguish between classes. As a result, the AUC obtained was 0.8414, indicating that the classifier distinguished correctly between all Positive and Negative class points.

Because it has two factors, 0 for non woody cover and 1 for woody cover, the response variable in the number structure had to be changed to factor. Data partitioning for training was 60 and 40 for validation, with 40% attributed to training data and 20% attributed to test data. When using the training dataset, a misclassification error of 0.0008 was obtained indicating woody cover and a misclassification error of 0.002 indicating non-woody cover. As a result, the actual misclassification error for training woody cover was 81, and the actual misclassification error for testing woody cover was 60 In order to confirm that the predictor variables are statistically significant, the study additionally looked at the model summary. The study then examined the model summary to determine which predictor variables are statistically significant. The Asterisk in the model summary guided which variables are significant with a confidence level of 0.95, which is 95 percent; and population, population per square, annual household income such as no income, income above the poverty line, below average income, average income, and middle average income were the variables with a confidence level of 0.95 p-value. Fig. 4.4 below, shows the ROC (The Receiver Operator Characteristic) and AUC (The Area Under the Curve) of logistic regression model for socioeconomic variables.

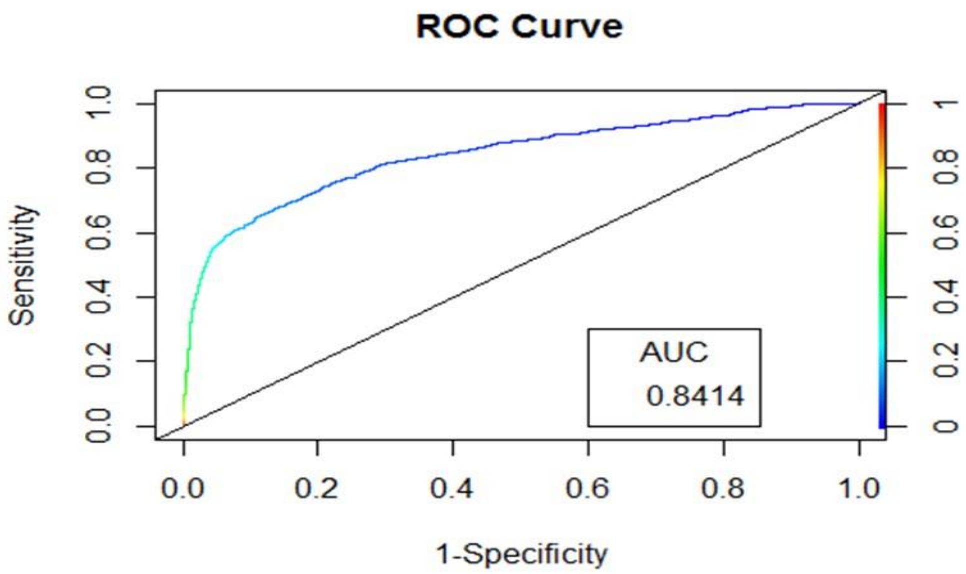

Fig. 4.4. ROC (The Receiver Operator Characteristic) and AUC (The Area Under the Curve) of the logistic regression model.

4.5. Selected variables for the combined model.

Table 4: A combination of both environmental and socio-economic variables as drivers of bush encroachment.

Environmental and Socioeconomic variables combined	P-Value	Estimation
Population density	0.985	-5.264e-01
Area per hectare	0.977	-3.026e-05
Nitrogen	0.971	8.680e-01
Employment (Employed)	0.982	7.229e-01
Temperature Maximum	0.993	-4.463e+02
Temperature Minimum	0.987	-6.786e+02
Temperature Mean	0.990	1.113e+03

Given that the logistic regression model's goodness of fit was 0 and its p-value was less than 0.05, it can be used to analyse factors connected to bush encroachment statistically significantly. On degrees of freedom 6228 and 6221, respectively, there was no deviation and some residual deviation. The estimates of the co-efficient for population density, area per hectare, minimum temperature, and maximum temperature were all less than 0.5, showing a weak correlation for bush invasion. As a result, co-efficient estimates for nitrogen, employed individuals, and temperature mean had results greater than 0.5, showing a higher association to bush invasion. In the study, model performance was also assessed using the ROC (Receiver Operator Characteristic) and AUC (Area Under the Curve) curves, binary classification issue evaluation metrics. The regression model's AUC of 0.997, which corresponds to the scenario above, shows that the classifier operated without error. Fig. 4.5 below, shows the ROC (The Receiver Operator Characteristic) and AUC (The Area Under the Curve) of logistic regression model for combined environmental and socioeconomic variables.

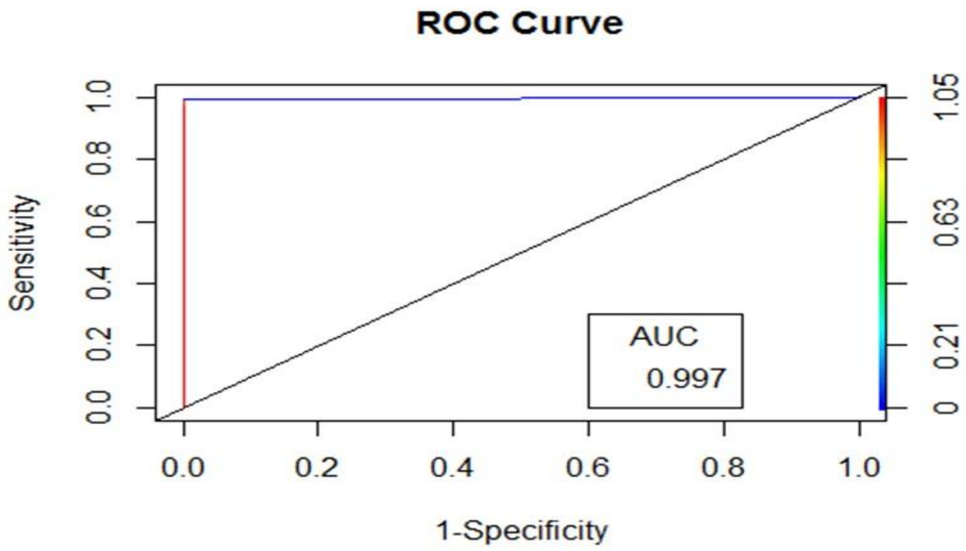

Fig. 4.5. ROC (The Receiver Operator Characteristic) and AUC (The Area Under the Curve) of the logistic regression model for combined environmental and socioeconomic variables.

4.6. Discussion

For the long-term management of a number of essential ecosystem services and processes, it is necessary to comprehend the spatiotemporal dynamics of tree cover in African savannas. Southern Africa's semi-arid savannas are extremely heterogeneous in space and time, making mapping difficult (Gaughan et al., 2013). The variation in grass and tree cover is influenced by a number of environmental and socioeconomic variables. For instance, it is expected that tree growth will be boosted by increasing levels of human carbon dioxide, which cause precipitation and photosynthesis (Kgope et al., 2010; Buitenwerf et al., 2012). This leads to bush encroachment, also known as the expansion of forests into grassland areas. The mapping of the flora in the province of Limpopo identified two classes: bush and grass. In many parts of the globe, socioeconomic and environmental variables are both affecting how grass and forest cover change over time (Mograbi et al., 2017).

The exploration of seasonal variability of bush encroachment using existing tree cover product was obtained from the CSIR and carried out with the goal of assessing bush encroachment and determining its potential drivers in the selected Limpopo province locations using remote sensing tree cover change data analysed by Cho and Ramoelo (2019). Higher resolution satellite remote sensing can be a more cost-effective tool for rangeland monitoring and management than traditional field survey methods, which are difficult, time-consuming, and expensive to implement, particularly in larger landscapes for land-cover assessment (Smit et al., 2011).

The findings of Cho and Ramoelo (2019) study were relevant to the study objectives. As a result, using the existing tree cover dataset, it was clear that there was an extension of bush encroachment in the Limpopo province between 2001 and 2018. The study also found that environmental and socioeconomic factors influence bush encroachment in the Limpopo province, which was accomplished by grouping all variables into three groups: environmental variables only, socioeconomic variables only, and a combination of both to determine which variables influenced bush encroachment in the Limpopo province between 2001 and 2018.The areas of hotspot in bush encroachment were identified and specified using the Kendall's Tau coefficient and the variables which were not statistically significant were omitted in the study.

The response variable, which contained two components of zero for non-woody cover and one for woody cover, had to be transformed from being a number structure into a factor before it could be used in a logistic regression model. Running a logistic regression model revealed that the chosen socioeconomic and environmental variables were significant to the study at a confidence level of 0.95, or 95%, with a factor of one (1) indicating a change in woody cover. The variables that were not significant to the study at a confidence level less than 0.95 with a factor of zero (0), which did not add explanation to the variance in the data and were ultimately omitted and found to be ineffective.

Several environmental and socioeconomic variables were excluded when using stepwise logistic regression because the model did not find them to be statistically significant, but those that were found to be statistically significant were included in the study results. Stepwise logistic regression was used to select the variables that were significant to the study and also used to eliminate the variables that were not significant. In the logistic regression model, a comparison of estimated environmental and socioeconomic variables results revealed a significant level of less than 0.05 for both environmental and socioeconomic variables result; and all variables considered in the model were correlated to tree cover change. However, certain factors did not show a significant difference and were eliminated from the study since their results revealed that the p-value was greater than 0.05; hence, there was no statistical evidence that the variables may be correlated to tree cover change. This suggests that the environmental and socioeconomic variables included in tables two (2) and three (3) of this study were positive drivers of bush encroachment in the Limpopo province between 2001 and 2018 time periods.

4.7. Management approaches

According to Smit et al., (1996), the primary goal of bush control is to bring tree populations to an ideal level so that the veld can be returned to a state of optimal grazing and browsing production while preserving ecological stability. According to Hoffman and Todd (1999), there are three methods that can be used to handle bush invasion: mechanical, chemical, and biological control. The study further recommends the method of debushing using mechanical means and brush packing as a restoration technology where stump is removed physically with a shovel, axe and digging bar which is the fastest and easiest mechanical way to mitigate bush encroachment. Beukes (1999), Visser (2007), Kellner (2008), Tongway & Ludwig (2011), and Pelser (2017) have all investigated the brush packing restoration technology to bring back quality of the savanna ecosystem.

This approach of protecting exposed surfaces from soil erosion effectively mimics the protective cover effect of plants (Kellner, 2013).

The following factors make brush packing an efficient technique for restoring savannas (Coetzee, 2005).

- It acts as a layer of protection against erosion caused by rain impact.
- It lowers soil temperature and helps to buffer temperature swings throughout the day.
- It helps keep soil moisture in the earth.
- The microenvironment for soil organisms and seedling plants is therefore improved.
- Grazing animals that frequently search for new development will be kept away from the developing plants.

CHAPTER 5

5.1. Synthesis, Conclusion and, Recommendations and Limitations of the study.

5.1.1. Synthesis

The Kendall's tau coefficient for tree cover was used to determine whether or not the area has bush encroachment. Environmental variables such as minimum temperature, mean temperature, and bulk density significantly explain the variability of bush encroachment in the Limpopo province, as do socioeconomic variables such as population density, education, employment, and income distributions. As a result, selected environmental and socioeconomic variables were found to be statistically significant to the study in the selected locations of the Limpopo province between 2001 and 2018 period, and the following study objectives were achieved:

i. To assess the extent of bush encroachment using existing remote sensing derived tree cover change product over a period between 2001 and 2018 in the Limpopo province.
ii. Determine environmental and socio-economic factors that influence bush encroachment in the Limpopo province.

5.1.2. Conclusion

Savannas are significant ecosystems with socioeconomic significance, according to Bourlière (1970), Belsky (1990), Scholes & Walker (1993), Scholes (1997), and Scholes & Archer (1997). They are composed of a mixture of trees and grasses. The most significant ecology for raising livestock is the African savanna (Bourlière, 1970; Lamprey, 1983). There has been growing evidence for the past 50 years that a phenomenon known as "bush encroachment" is changing savannas all across the world (Archer et al., 1995). Throughout rangelands throughout the world, including in Africa, the impact of bush encroachment is a typical type of land degradation. Our knowledge of the dynamics of bush encroachment can be expanded because controlling it calls for an improved comprehension of the underlying causes and coordinated management strategies. Future studies on the impact of bush encroachment should take into account several variables because there are few thorough studies that investigate the dynamics of woody vegetation across a variety of environmental conditions (e.g., Sankaran et al., 2008).

Environmental factors such as minimum temperature, mean temperature, and bulk density contribute to bush encroachment in the Limpopo province, as do socioeconomic factors such as population density, and annual household income levels such as no income, income above poverty line, income below average, average income; and middle average income. Therefore, the areas of hotspot were identified to determine which areas in the Limpopo province have been mostly affected by bush encroachment between 2001 and 2018 periods; and the Capricorn and Waterberg district municipalities were the mostly affected compared to other areas in the province.

The logistic regression method was used to analyse environmental and socioeconomic variables associated with bush encroachment in the Limpopo province. A logistic regression model that proved to be a useful tool for detecting key indicators of tree cover change under a variety of possible correlates, was used as a statistical method to determine whether environmental and socioeconomic variables contribute to bush encroachment. The environmental and socioeconomic variables in the model further explain a significant portion of the variance in the tree cover data, indicating that environmental and socioeconomic factors are a major driving force of the impact of bush encroachment in the Limpopo province.

5.1.3. Recommendations of the study

As a result, remote sensing technology is recommended for monitoring bush encroachment in the Limpopo province. For many years, data from remote sensing has been utilized to track bush encroachment. Using remote sensing data is simple and offers several benefits over conventional approaches (Dube & Mutanga, 2015; Dougill et al., 2016). It is suggested that the following factors be prioritized for future research and assessment:

i. use of synthetic aperture RADAR (SAR), e.g., Sentinel-1 in the improvement of tree cover layer, or even testing the integration of Optical and SAR data
ii. Improve the spatial resolution of the tree cover product using 30m Sentinel-1 data

iii. Texture metrics derived from optical and SAR images should be tested in the mapping of bush encroachment.

5.1.4. Limitations of the study

The study period was limited for the years between 2001 and 2018, as a result, longer-term data are needed to fully assess the recovery of tree cover change and the impact of bush encroachment on the savanna ecosystem.

CHAPTER 6

REFERENCES

Aleman, J.C., Blarquez, O. and Staver, C.A., 2016. Land-use change outweighs projected effects of changing rainfall on tree cover in sub-Saharan Africa. *Global change biology*, *22*(9), pp.3013-3025.

Allsopp, N., Laurent, C., Debeaudoin, L.M. and Samuels, M.I., 2007. Environmental perceptions and practices of livestock keepers on the Namaqualand Commons challenge conventional rangeland management. *Journal of Arid Environments*, *70*(4), pp.740-754.

Anadón, J.D., Sala, O.E., Turner, B.L. and Bennett, E.M., 2014. Effect of woody-plant encroachment on livestock production in North and South America. *Proceedings of the National Academy of Sciences*, *111*(35), pp.12948-12953.

Angassa, A., 2005. The ecological impact of bush encroachment on the yield of grasses in Borana rangeland ecosystem. *African Journal of Ecology*, *43*(1), pp.14-20.

Angassa, A. and Oba, G., 2007. Relating long-term rainfall variability to cattle population dynamics in communal rangelands and a government ranch in southern Ethiopia. *Agricultural systems*, *94*(3), pp.715-725.

Angassa, A. and Oba, G., 2008. Herder perceptions on impacts of range enclosures, crop farming, fire ban and bush encroachment on the rangelands of Borana, Southern Ethiopia. *Human ecology*, *36*(2), pp.201-215.

Ayelew, S. and Mulualem, G., 2018. A review on bush encroachment effect on cattle rearing in rangelands. *Journal of Rangeland Science*, *8*(4), pp.403-415.

Archer, S., 1995. Tree-grass dynamics in a Prosopis-thornscrub savanna parkland:

reconstructing the past and predicting the future. *Ecoscience*, *2*(1), pp.83-99.

Archer, S., Boutton, T.W. and Hibbard, K.A., 2001. Trees in grasslands: biogeochemical consequences of woody plant expansion. In *Global biogeochemical cycles in the climate system* (pp. 115-137). Academic Press.

Archibald, S. and Scholes, R.J., 2007. Leaf green-up in a semi-arid African savannaseparating tree and grass responses to environmental cues. *Journal of Vegetation Science*, *18*(4), pp.583-594.

Ayelew, S., and Mulualem, G. 2018. A review on bush encroachment effect on cattle rearing in rangelands. *Journal of Rangeland Science, 8*(4), 403-415.

Bamford, A.J., Diekmann, M., Monadjem, A. and Mendelsohn, J., 2007. Ranging behaviour of Cape Vultures Gyps coprotheres from an endangered population in Namibia. *Bird Conservation International*, *17*(4), pp.331-339.

Barac, A.S., 2003. *EcoRestore: a decision support system for the restoration of degraded rangelands in southern Africa* (Doctoral dissertation, North-West University).

Bart, D., 2006. Integrating local ecological knowledge and manipulative experiments to find the causes of environmental change. *Frontiers in Ecology and the Environment*, *4*(10), pp.541-546.

Baumann, M., Levers, C., Macchi, L., Bluhm, H., Waske, B., Gasparri, N.I. and

Kuemmerle, T., 2018. Mapping continuous fields of tree and shrub cover across the Gran Chaco using Landsat 8 and Sentinel-1 data. *Remote sensing of environment*, *216*, pp.201-211.

Belsky, J., 1990. Parental and nonparental child care and children's socioemotional development: A decade in review. *Journal of Marriage and the Family*, pp.885-903.

Berry, R.S. and Kulmatiski, A., 2017. A savanna response to precipitation intensity. *PloS one*, *12*(4), p.e0175402.

Beukes, P.C., 1999. Livestock impact assessment and restoration strategies in the semi-arid Karoo.

Booth, C.A., Sanchez-Bayo, F. and King, G.W., 1996. Establishment of woody weeds in western New South Wales. 2. Growth and competitive potential. *The Rangeland Journal*, *18*(1), pp.80-98.

Bond, W.J. and Wilgen, B.W.V., 1996. Plant demography and fire II. Event-dependent effects. In *Fire and plants* (pp. 88-122). Springer, Dordrecht.

Bourlière, F. and Hadley, M., 1970. The ecology of tropical savannas. *Annual review of Ecology and Systematics*, *1*(1), pp.125-152.

Belayneh, A. and Tessema, Z.K., 2017. Mechanisms of bush encroachment and its inter-connection with rangeland degradation in semi-arid African ecosystems: a review. *Journal of Arid Land*, *9*(2), pp.299-312.

Belsky, A.J., 1990. Tree/grass ratios in East African savannas: a comparison of existing models. *Journal of biogeography*, pp.483-489.

Buitenwerf, R., Bond, W.J., Stevens, N. and Trollope, W., 2012. Increased tree densities in S outh A frican savannas:> 50 years of data suggests CO 2 as a driver. *Global Change Biology*, *18*(2), pp.675-684.

Case, M.F. and Staver, A.C., 2017. Fire prevents woody encroachment only at higherthan-historical frequencies in a South African savanna. *Journal of Applied Ecology*, *54*(3), pp.955-962.

Ceulemans, R., Janssens, I.A. and Jach, M.E., 1999. Effects of CO 2 enrichment on trees and forests: lessons to be learned in view of future ecosystem studies. *Annals of Botany*, *84*(5), pp.577-590.

Cha, S., Chae, H.M., Lee, S.H. and Shim, J.K., 2017. Effect of elevated atmospheric CO_2 concentration on growth and leaf litter decomposition of Quercus acutissima and Fraxinus rhynchophylla. *PLoS One*, *12*(2), p.e0171197.

Charis, G., Danha, G., and Muzenda, E. 2019. Waste valorisation opportunities for bush encroacher biomass in savannah ecosystems: A comparative case analysis of Botswana and Namibia. *Procedia Manufacturing*, 35, 974- 979.

Cho, M.A., Ramoelo, A. and Dziba, L., 2017. Response of land surface phenology to variation in tree cover during green-up and senescence periods in the semi-arid savanna of Southern Africa. *Remote Sensing*, *9*(7), p.689.

Cho, M.A. and Ramoelo, A., 2019. Optimal dates for assessing long-term changes in tree-cover in the semi-arid biomes of South Africa using MODIS NDVI time series (2001–2018). *International Journal of Applied Earth Observation and Geoinformation*, *81*, pp.27-36.

Coetzee, K., 2005. *Caring for natural rangelands*. University of KwaZulu-Natal Press.

Conover, W.J., 1980. Practical Nonparametric Statistics, by John Wiley and Sons Inc. *New York*, *2*.

Cohen, J., 1960. A coefficient of agreement for nominal scales. *Educational and psychological measurement*, *20*(1), pp.37-46.

Crichton, N.J., 1999. Information point: Spearman's rank correlation. *Journal of clinical nursing*, *8*(7), pp.763-766.

Dalle, G., Maass, B.L. and Isselstein, J., 2006. Encroachment of woody plants and its impact on pastoral livestock production in the Borana lowlands, southern Oromia, Ethiopia. *African Journal of Ecology*, *44*(2), pp.237-246.

De Beer, J.D., Dryer, J., Loubser, C., 2005. Environmental issues and risks. In: *Environmental Education, Some South African Perspectives* (Ed. C. P.Loubser). Van Schaik Publishers, Pretoria.

De Klerk, J.N., 2004. *Bush encroachment in Namibia: Report on phase 1 of the bush encroachment research, monitoring, and management project*. Ministry of Environment and Tourism, Directorate of Environmental Affairs.

Desert Research Foundation of Namibia (DRFN). 2009. *Combating bush encroachment for Namibia's development (CBEND)*. Windhoek, Namibia: Desert Research Foundation of Namibia.

Dougill, A.J., Akanyang, L., Perkins, J.S., Eckardt, F.D., Stringer, L.C., Favretto, N., Atlhopheng, J. and Mulale, K., 2016. Land use, rangeland degradation and ecological changes in the southern Kalahari, Botswana. *African Journal of Ecology*, *54*(1), pp.59-
67.

Dickhoefer, U., Buerkert, A., Brinkmann, K. and Schlecht, E., 2010. The role of pasture management for sustainable livestock production in semi-arid subtropical mountain regions. *Journal of Arid Environments*, *74*(8), pp.962-972.

Donaldson, C.H., 1969. Bush encroachment and methods of control with special reference to the Blackthorn (Acacia mellifera) problem of the Molopo area. *Armoedsvlakte research station, Vryburg*.

Dube, T. and Mutanga, O., 2015. Evaluating the utility of the medium-spatial resolution Landsat 8 multispectral sensor in quantifying aboveground biomass in uMgeni catchment, South Africa. *ISPRS Journal of Photogrammetry and Remote Sensing*, *101*, pp.36-46.

Dube, T., Pandit, S., Shoko, C., Ramoelo, A., Mazvimavi, D. and Dalu, T., 2019. Numerical assessments of leaf area index in tropical savanna rangelands, South Africa using Landsat 8 OLI derived metrics and in-situ measurements. *Remote Sensing*, *11*(7), p.829.

Eldridge, D.J., Wilson, B.R. and Oliver, I., 2003. Regrowth and soil erosion in the semi-arid woodlands of New South Wales. *NSW Department of Land and Water Conservation, Sydney*.

Eldridge, D.J., Bowker, M.A., Maestre, F.T., Roger, E., Reynolds, J.F. and Whitford, W.G., 2011. Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis. *Ecology letters*, *14*(7), pp.709-722.

Ellis, J.E. and Swift, D.M., 1988. Stability of African pastoral ecosystems: alternate paradigms and implications for development. *Rangeland Ecology & Management/Journal of Range Management Archives*, *41*(6), pp.450-459.

Ehrenfeld, J.G., 2000. Defining the limits of restoration: the need for realistic goals. *Restoration ecology*, *8*(1), pp.2-9.

Erreygers, G., 2013. A dual Atkinson measure of socioeconomic inequality of health. *Health economics*, *22*(4), pp.466-479.

Feller, S., Mahony, J., Sanzanowicz, R. and Wise, J., 2006. *Development of bush blocks industry in Nambia and interactive qualifying project report*. BSc thesis. Faculty of Worcester Polytecnic Institute. Namibia

Friedl, M.A., McIver, D.K., Hodges, J.C., Zhang, X.Y., Muchoney, D., Strahler, A.H., Woodcock, C.E., Gopal, S., Schneider, A., Cooper, A. and Baccini, A., 2002. Global land cover mapping from MODIS: algorithms and early results. *Remote sensing of Environment*, *83*(1-2), pp.287-302.

Fritz, S., See, L. and Rembold, F., 2010. Comparison of global and regional land cover maps with statistical information for the agricultural domain in Africa. *International Journal of Remote Sensing*, *31*(9), pp.2237-2256.

Fulbright, T.E., 1996. a theoretical basis for planning woody plant control to maintain species diversity. *Rangeland Ecology & Management/Journal of Range Management Archives*, *49*(6), pp.554-559.

Gibbens, R.P., McNeely, R.P., Havstad, K.M., Beck, R.F. and Nolen, B., 2005. Vegetation changes in the Jornada Basin from 1858 to 1998. *Journal of Arid Environments*, *61*(4), pp.651-668.

Gignoux, J., Lahoreau, G., Julliard, R. and Barot, S., 2009. Establishment and early persistence of tree seedlings in an annually burned savanna. *Journal of Ecology*, *97*(3), pp.484-495.

Gil-Romera, G., Lamb, H.F., Turton, D., Sevilla-Callejo, M. and Umer, M., 2010. Longterm resilience, bush encroachment patterns and local knowledge in a Northeast African savanna. *Global Environmental Change*, *20*(4), pp.612-626.

Gillson, L., 2004. Testing non-equilibrium theories in savannas: 1400 years of vegetation change in Tsavo National Park, Kenya. *Ecological Complexity*, *1*(4), pp.281-298.

Gong, P., Wang, J., Yu, L., Zhao, Y., Zhao, Y., Liang, L., Niu, Z., Huang, X., Fu, H., Liu, S. and Li, C., 2013. Finer resolution observation and monitoring of global land cover: First mapping results with Landsat TM and ETM+ data. *International Journal of Remote Sensing*, *34*(7), pp.2607-2654.

Graw, V., Dubovyk, O. and Piroska, R., 2017, July. Bush encroachment detection in Africa—A multi-scale approach. In *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (pp. 4270-4273). IEEE.

Hansen, M.C., DeFries, R.S., Townshend, J.R. and Sohlberg, R., 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. *International journal of remote sensing*, *21*(6-7), pp.1331-1364.

Hardin, G., 1968. The tragedy of the commons Science 162 (3859): 1243–1248. *Find this article online*.

Higgins, S.I., Bond, W.J., February, E.C., Bronn, A., Euston-Brown, D.I., Enslin, B., Govender, N., Rademan, L., O'Regan, S., Potgieter, A.L. and Scheiter, S., 2007. Effects of four decades of fire manipulation on woody vegetation structure in savanna. *Ecology*, *88*(5), pp.1119-1125.

Fatunbi AO, Johan MS, Dube S (2008) Long-term effects of different burning frequencies on the dry savannah grassland in South Africa. *African Journal of Agricultural Research* 3, 147-153.

Grossman, D., Gander, M. V., 1989. Land transformation in South African savannah regions. *South African Geographical Journal*, 71, pp. 38-45.

Hill, J., Stellmes, M., Udelhoven, T., Röder, A. and Sommer, S., 2008. Mediterranean desertification and land degradation: Mapping related land use change syndromes based on satellite observations. *Global and Planetary Change*, *64*(3-4), pp.146-157.

Hoffman, T. and Todd, S., 1999. Vegetation degradation. *Land Degradation in South Africa. South African National Biodiversity Institute, Cape Town, South Africa*.

Hobbs, R.J., 2007. Setting effective and realistic restoration goals: key directions for research. *Restoration ecology*, *15*(2), pp.354-357.

Huang, C.Y., Archer, S.R., McClaran, M.P. and Marsh, S.E., 2018. Shrub encroachment into grasslands: end of an era? *PeerJ*, *6*, p.e5474.

Hudak, A.T., 1999. Rangeland mismanagement in South Africa: failure to apply ecological knowledge. *Human Ecology*, *27*(1), pp.55-78.

Joubert, D.F., 2003. The impact of bush control measures on the ecological environment (biodiversity, habitat diversity and landscape considerations.). *Unpublished specialist report prepared for the Ministry of Environment and Tourism, Windhoek*.

Joubert, D.F., Rothauge, A. and Smit, G.N., 2008. A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by Acacia mellifera. *Journal of Arid Environments*, *72*(12), pp.22012210.

Joubert, D.F., Smit, G.N. and Hoffman, M.T., 2013. The influence of rainfall, competition and predation on seed production, germination and establishment of an encroaching Acacia in an arid Namibian savanna. *Journal of Arid Environments*, *91*, pp.7-13.

Kellner, K., 2008. *Studies in land degradation, desertification and restoration ecology: Challenges and opportunities*. Potchefstroom: Noordwes-Universiteit, Potchefstroomkampus (Suid-Afrika).

Kellner, K., Mangani, R., Sebitloane, T., Chirima, J., Meyer, N., Coetzee, H., Malan, P. and Koch, J., 2013. General principles for the rehabilitation of degraded semi-arid rangelands. *North-West University*.

Kerley, G.I., Knight, M.H. and De Kock, M., 1995. Desertification of subtropical thicket in the Eastern Cape, South Africa: are there alternatives?. *Environmental Monitoring and Assessment*, *37*, pp.211-230.

Kgope, B.S., Bond, W.J. and Midgley, G.F., 2010. Growth responses of African savanna trees implicate atmospheric [CO2] as a driver of past and current changes in savanna tree cover. *Austral Ecology*, *35*(4), pp.451-463.

Kgosikoma, O., Mojeremane, W. and Harvie, B.A., 2012. Pastoralists' perception and ecological knowledge on savanna ecosystem dynamics in semi-arid Botswana. *Ecology and Society*, *17*(4).

Knoop, W.T. and Walker, B.H., 1985. Interactions of woody and herbaceous vegetation in a southern African savanna. *The Journal of Ecology*, pp.235-253.

Kraaij, T. and Ward, D., 2006. Effects of rain, nitrogen, fire and grazing on tree recruitment and early survival in bush-encroached savanna, South Africa. *Plant Ecology*, *186*(2), pp.235-246.

Kruger, B., 2002. Bush encroachment Research, Monitoring and Management Project-(BERMMP): Bio-physical and Socio-economic impact of Bush Encroachment in the-Communal areas of Namibia. *Desert Research Foundation of Namibia, Windhoek*.

Lamprey, H.F., 1983. Pastoralism yesterday and today: the over-grazing problem. *Ecosystems of the World*.

Larcher, W. 1983. *Physiological plant ecology*. In V. Springer, B. Mendelsohn J, A. Jarvis, C. Roberts and T. Robertson 2002. Atlas of Namibia: A portrait of the land and its people. New Africa Books (Pty) Ltd. Cape Town.

LECHMERE-OERTEL, R.G., Cowling, R.M. and Kerley, G.I., 2005. Landscape dysfunction and reduced spatial heterogeneity in soil resources and fertility in semi-arid succulent thicket, South Africa. *Austral Ecology*, *30*(6), pp.615-624.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, Z., Yang, L.W.M.J. and Merchant, J.W., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *International journal of remote sensing*, *21*(6-7), pp.1303-1330.

Madonsela, S., Cho, M.A., Mathieu, R., Mutanga, O., Ramoelo, A., Kaszta, Ż., Van De Kerchove, R. and Wolff, E., 2017. Multi-phenology WorldView-2 imagery improves remote sensing of savannah tree species. *International Journal of Applied Earth Observation and Geoinformation*, *58*, pp.65-73.

Maestre, F.T., Bowker, M.A., Puche, M.D., Belén Hinojosa, M., Martínez, I., García-Palacios, P., Castillo, A.P., Soliveres, S., Luzuriaga, A.L., Sánchez, A.M. and Carreira, J.A., 2009. Shrub encroachment can reverse desertification in semi-arid Mediterranean grasslands. *Ecology letters*, *12*(9), pp.930-941.

Mapekula, M., 2009. *Milk production and calf performance in Nguni and crossbred cattle raised on communal rangelands of the Eastern Cape Province of South Africa* (Doctoral dissertation, University of Fort Hare).

McNally, A., Shukla, S., Arsenault, K.R., Wang, S., Peters-Lidard, C.D. and Verdin, J.P., 2016. Evaluating ESA CCI soil moisture in East Africa. *International Journal of Applied Earth Observation and Geoinformation*, *48*, pp.96-109.

McCullagh, P., & Nelder, J. A. (1983). *Generalized linear models*. New York: Chapman and Hall.

Menzel, S. and Teng, J., 2010. Ecosystem services as a stakeholder-driven concept for conservation science. *Conservation Biology*, *24*(3), pp.907-909.

Ministry of Agriculture, Water and Forestry (MAWF). 2014*. Baseline assessment for the debushing programme in Namibia.* Windhoek, Namibia: Republic of Namibia.

Moleele, N.M. and Perkins, J.S., 1998. Encroaching woody plant species and boreholes: is cattle density the main driving factor in the Olifants Drift communal grazing lands, south-eastern Botswana?. *Journal of Arid Environments*, *40*(3), pp.245-253.

Moleele, N.M., Ringrose, S., Matheson, W. and Vanderpost, C., 2002. More woody plants? The status of bush encroachment in Botswana's grazing areas. *Journal of Environmental Management*, *64*(1), pp.3-11.

Mograbi, P.J., Asner, G.P., Witkowski, E.T., Erasmus, B.F., Wessels, K.J., Mathieu, R. and Vaughn, N.R., 2017. Humans and elephants as treefall drivers in African savannas. *Ecography*, *40*(11), pp.1274-1284.

Mphinyane, W.N., Tacheba, G., Mangope, S. and Makore, J., 2008. Influence of stocking rate on herbage production, steers livemass gain and carcass price on semiarid sweet bushveld in Southeren Botswana. *Afr. J. Agric. Res*, *3*, pp.084-090.

Mulualem, Y.F. and Chandravanshi, B.S., 2021. Assessment of metals content of widely used traditional toothbrushes in Addis Ababa, Ethiopia. *Bulletin of the Chemical Society of Ethiopia*, *35*(2), pp.257-272.

Mutetwa, R., Boehme, C., Dimairo, M., Bandason, T., Munyati, S.S., Mangwanya, D., Mungofa, S., Butterworth, A.E., Mason, P.R. and Corbett, E.L., 2009. Diagnostic accuracy of commercial urinary lipoarabinomannan detection in African tuberculosis suspects and patients. *The international journal of tuberculosis and lung disease*, *13*(10), pp.1253-1259.

National Drought Task Force. 1997. Towards a drought policy for Namibia. *A discussion document prepared by the National Drought Task Force for a workshop at Neudamm Agricultural College 11-13 March 1997*. Windhoek, Namibia: National Drought Task Force.

Namibia Agricultural Union (NAU). 2010. The effect of bush encroachment on groundwater resources in Namibia: A desk top study. Windhoek, Namibia: Namibia Agricultural Union. Retrieved from http://www.agrinamibia.com.na/wpcontent/uploads/2018/02/

Nelder, J.A. and Wedderburn, R.W., 1972. Generalized linear models. *Journal of the Royal Statistical Society: Series A (General)*, *135*(3), pp.370-384.

Noble, J.C., 1998. *The Delicate and Noxious Scrub: Csiro Studies on Native Tree and Shrubproliferation in the Semi-Arid Woodlands of Eastern Australia*. Csiro Publishing.

Oba, G., Post, E., Syvertsen, P.O. and Stenseth, N.C., 2000. Bush cover and range condition assessments in relation to landscape and grazing in southern Ethiopia. *Landscape Ecology*, *15*(6), pp.535-546.

O'connor, T.G., Puttick, J.R. and Hoffman, M.T., 2014. Bush encroachment in southern Africa: changes and causes. *African Journal of Range & Forage Science*, *31*(2), pp.67-88.

Oldeland, J., Dorigo, W., Wesuls, D. and Jürgens, N., 2010. Mapping bush encroaching species by seasonal differences in hyperspectral imagery. *Remote Sensing*, *2*(6), pp.1416-1438.

Olson, R.A. and Whitson, T.D., 2002. Restoring structure in late-successional sagebrush communities by thinning with tebuthiuron. *Restoration Ecology*, *10*(1), pp.146-155.

Pelser, J.J., 2017. *Evaluation of selected restoration technologies in degraded areas of the Mokala National Park, South Africa* (Doctoral dissertation, North-West University (South Africa)).

Pratt, L.A., Hsing, W., Gibson, K.E. and Silhavy, T.J., 1996. From acids to osmZ: multiple factors influence synthesis of the OmpF and OmpC porins in Escherichia coli. *Molecular microbiology*, *20*(5), pp.911-917.

Rohde, R.F. and Hoffman, M.T., 2012. The historical ecology of Namibian rangelands: Vegetation change since 1876 in response to local and global drivers. *Science of the Total Environment*, *416*, pp.276-288.

Roques, K.G., O'connor, T.G. and Watkinson, A.R., 2001. Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall and density dependence. *Journal of Applied Ecology*, *38*(2), pp.268-280.

Sankaran, M., Hanan, N.P., Scholes, R.J., Ratnam, J., Augustine, D.J., Cade, B.S., Gignoux, J., Higgins, S.I., Le Roux, X., Ludwig, F. and Ardo, J., 2005. Determinants of woody cover in African savannas. *Nature*, *438*(7069), pp.846-849.

Sankaran, M., Ratnam, J. and Hanan, N., 2008. Woody cover in African savannas: the role of resources, fire and herbivory. *Global Ecology and Biogeography*, *17*(2), pp.236-245.

Scott, L., Cooremans, B., De Wet, J.S. and Vogel, J.C., 1991. Holocene environmental changes in Namibia inferred from pollen analysis of swamp and lake deposits. *The Holocene*, *1*(1), pp.8-13.

Sedano, F., Gong, P. and Ferrao, M., 2005. Land cover assessment with MODIS imagery in southern African Miombo ecosystems. *Remote sensing of environment*, *98*(4), pp.429-441.

Sexton, J.O., Song, X.P., Feng, M., Noojipady, P., Anand, A., Huang, C., Kim, D.H., Collins, K.M., Channan, S., DiMiceli, C. and Townshend, J.R., 2013. Global, 30-m resolution continuous fields of tree cover: Landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error. *International Journal of Digital Earth*, *6*(5), pp.427-448.

Shantz, H.L. and Turner, B.L., 1958. Photographic documentation of vegetational changes in Africa over a third of a century. *Photographic documentation of vegetational changes in Africa over a third of a century.*

Scholes, R.J. and Walker, B.H., 1993. *An African savanna: synthesis of the Nylsvley study*. Cambridge University Press.

Scholes, R.J. and Archer, S.R., 1997. Tree-grass interactions in savannas. *Annual review of Ecology and Systematics*, pp.517-544.

Schröter, M., Jakoby, O., Olbrich, R., Eichhorn, M. and Baumgärtner, S., 2011. Remote sensing of bush encroachment on commercial cattle farms in semi-arid rangelands in Namibia. In *Environmental Modeling for Sustainable Regional Development: System Approaches and Advanced Methods* (pp. 327-343). IGI Global.

Sive, T., 2016. Evaluating farmers' perceptions and the impact of bush encroachment on herbaceous vegetation and soil nutrients in Sheshegu communal rangelands of Eastern Cape, South Africa. *University of Fort Hare, Alice, South Africa. Search in*.

Skarpe, C., 1990. Shrub layer dynamics under different herbivore densities in an arid savanna, Botswana. *Journal of Applied Ecology*, pp.873-885.

Smit, N., 1999. *Guide to the acacias of South Africa*. Briza Publications.

Smith, B. Samuelsson, P. Wramneby, A. and M. Rummukainen. *2011 A model of the compiled dynamics of climates, vegetation and terrestrial ecosystem biogeochemistry for regional applications.* Tell us A 63:87-106.

Sop, T.K. and Oldeland, J., 2013. Local perceptions of woody vegetation dynamics in the context of a 'greening Sahel': a case study from Burkina Faso. *Land Degradation & Development*, *24*(6), pp.511-527.

Spinage, C.A., 2012. *African ecology: benchmarks and historical perspectives*. Springer Science & Business Media.

Squires, V.R., Mann, T.L. and Andrew, M.H., 1992. Problems in implementing improved range management on common lands in Africa: an Australian perspective. *Journal of the Grassland Society of Southern Africa*, *9*(1), pp.1-7.

Symeonakis, E., Petroulaki, K. and Higginbottom, T., 2016. Landsat-based woody vegetation cover monitoring in southern African savannahs. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *41*, pp.563-567.

Tainton, N.M. 1999. *Veld management in Southern Africa*. Pietermaritzburg:University of Natal Press Technical paper 20. ISRIC, Wageningen, the Netherlands.

Tateishi, R., Uriyangqai, B., Al-Bilbisi, H., Ghar, M.A., Tsend-Ayush, J., Kobayashi, T., Kasimu, A., Hoan, N.T., Shalaby, A., Alsaaideh, B. and Enkhzaya, T., 2011. Production of global land cover data–GLCNMO. *International Journal of Digital Earth*, *4*(1), pp.22-49.

Tews, J. and Jeltsch, F., 2004. Modelling the impact of climate change on woody plant population dynamics in South African savanna. *BMC ecology*, *4*(1), pp.1-12.

Tongway, D.J. and Ludwig, J.A., 2011. *Restoring disturbed landscapes: putting principles into practice*. Island Press.

Troth, J.L., Lowery, R.F. and Fallis, F.G., 1986. Herbicides as cut-stump treatments during precommercial thinning. *Proceedings-Southern Weed Science Society (USA)*.

United Nations Framework Convention on Climate Change (UNFCCC). 2010. Namibia second national communication to the United Nations framework convention on climate change. Windhoek, Namibia: Republic of Namibia.

Van Oudshoorn, N., Saetnan, A.R. and Lie, M., 2002, July. On gender and things:

Reflections on an exhibition on gendered artifacts. In *Women's Studies International Forum* (Vol. 25, No. 4, pp. 471-483). Pergamon.

Van Auken, O.W., 2000. Shrub invasions of North American semiarid grasslands. *Annual review of ecology and systematics*, *31*(1), pp.197-215.

Van Auken, O.W., 2009. Causes and consequences of woody plant encroachment into western North American grasslands. *Journal of environmental management*, *90*(10), pp.2931-2942.

van Rooyen, M.W., le Roux, A., van der Merwe, H., van Rooyen, N. and Geldenhuys, C., 2018. Long-term vegetation change (> 20 years) in the plains habitat on the Goegap Nature Reserve, Succulent Karoo, South Africa. *African Journal of Range & Forage Science*, *35*(3-4), pp.289-302.

Van Vegten, J.A., 1984. Thornbush invasion in a savanna ecosystem in eastern Botswana. *Vegetatio*, *56*(1), pp.3-7.

Visser, N., Morris, C., Hardy, M.B. and Botha, J.C., 2007. Restoring bare patches in the Nama-Karoo of South Africa. *African Journal of Range and Forage Science*, *24*(2), pp.87-96.

Vogel, M. and Strohbach, M., 2009, July. Monitoring of savanna degradation in Namibia using Landsat TM/ETM+ data. In *2009 IEEE International Geoscience and Remote Sensing Symposium* (Vol. 3, pp. III-931). IEEE.

Walker, B.H., Ludwig, D., Holling, C.S. and Peterman, R.M., 1981. Stability of semiarid savanna grazing systems. *The Journal of Ecology*, pp.473-498.

Walter, H. and Burnett, J.H., 1971. *Ecology of tropical and subtropical vegetation* (Vol. 539, pp. xviii+-539). Edinburgh: Oliver and Boyd.

Ward, D. and Young, T.P., 2002. Effects of large mammalian herbivores and ant symbionts on condensed tannins of Acacia drepanolobium in Kenya. *Journal of Chemical Ecology*, *28*(5), pp.921-937.

Ward, D., 2005. Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, *22*(2), pp.101-105.

Ward, D.A.V.I.D., 2006. Long-term effects of herbivory on plant diversity and functional types in arid ecosystems. *CONSERVATION BIOLOGY SERIES-CAMBRIDGE-*, *11*, p.142.

Ward, D., 2010. A resource ratio model of the effects of changes in CO2 on woody
Welz, A., 2013. The Surprising Role of CO2 Changes on the African
Savanna. *Environment*, *360*.plant invasion. *Plant Ecology*, *209*(1), pp.147-152.

Westoby, M., Walker, B. and Noy-Meir, I., 1989. Opportunistic management for rangelands not at equilibrium. *Rangeland Ecology & Management/Journal of Range Management Archives*, *42*(4), pp.266-274.

Wiegand, K., Ward, D. and Saltz, D., 2005. Multi-scale patterns and bush encroachment in an arid savanna with a shallow soil layer. *Journal of vegetation science*, *16*(3), pp.311-320.

Wiegand, K., Saltz, D. and Ward, D., 2006. A patch-dynamics approach to savanna dynamics and woody plant encroachment–insights from an arid savanna. *Perspectives in Plant Ecology, Evolution and Systematics*, *7*(4), pp.229-242.

Wigley, B.J., Bond, W.J. and Hoffman, M.T., 2009. Bush encroachment under three contrasting land-use practices in a mesic South African savanna. *African Journal of Ecology*, *47*, pp.62-70.

Worku, B., 2018. Effect of post bush clearing management practice on herbaceous species productivity and soil status of rangelands in Hammer district of South Omo zone. *J. Agric. Sci. Food Res.*, *9*(229), p.2.