Understanding social-ecological regime shifts: the case of woody encroachment in South Africa

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Declaration

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Abstract

Humanity has been very successful in modifying the planet to meet the demands of a rapidly growing human population. As human activities have grown in magnitude, they have become increasingly interlinked with ecosystem dynamics, creating social-ecological systems (SES). Increased human impacts on ecosystems are also leading to an increased occurrence of regime shifts: large, persistent changes in the structure and function of ecosystems and SES that often have substantive impacts on the suite of ecosystem services provided by these systems, and on the well-being of people who live in them. As global changes accelerate, better understanding the drivers, impacts and risks of regime shifts has become a key need. This knowledge has important implications for the formulation of management strategies that aim to either maintain existing desirable regimes, restore previous regimes where a regime shift has occurred, or facilitate transformation to new regimes in the novel planetary conditions we face.

A prevalent regime shift in savannas worldwide is woody encroachment. Woody encroachment is a shift from a grassy savanna to a persistently woody savanna, and has direct implications for a variety of ecosystem services such as livestock grazing, and people's livelihoods that depend on these services. Much of the work on woody encroachment has focused on the direct drivers of the process, such as the role of fire or grazing in inhibiting or promoting encroachment. However, less is understood about how underlying social processes may impact these drivers, how ecological changes may feedback to affect some of these underlying social processes, how to monitor woody encroachment as a regime shift and how encroachment impacts ecosystem services and human well-being.

This dissertation consists of four research chapters in journal format. The first is a synthesis of the ecological drivers and the social processes and drivers of woody encroachment based on the published literature, synthesized using causal loop diagrams and a published regime shift analysis framework. The remainder of the papers focus on woody encroachment in the Hlabisa district of South Africa. The second paper used Landsat TM imagery to quantify the extent of woody encroachment from 1990 to 2016 under contrasting land uses, specifically state-owned conservation land and communal land largely used for subsistence agriculture. The third paper builds on paper 2 and used spatial autocorrelation and the sequential t-tests analysis for regime shifts (STARS) to explore whether the changes observed in the remote sensing data conform to the statistical properties of a regime shift. The fourth paper used semi-structured interviews

to investigate how different land users in the Hlabisa area (state conservation game reserve, private game reserves and local communities) are impacted by woody encroachment.

Paper 1 provides a broader social-ecological understanding of woody encroachment. This review highlighted the link between increased human populations (locally and globally) and woody encroachment, and suggests key management options based on the key feedback loops identified. Paper 2 and 3 highlight the value of multi-temporal remote sensing data to monitor the extent of woody encroachment and collect time series data that could be used in the detection of regime shifts and early warning indicator of these shifts. Paper 2 found that Hlabisa experienced significant increases in tree cover between 1990 and 2016, under both the conservation and communal land uses, suggesting that the changes may be largely driven by global drivers rather than local land use practices. Paper 3 shows that these tree cover changes constituted a regime shift, confirmed through the results of STARS and spatial autocorrelation. This paper also suggests that these approaches offer a method that could be used to monitor woody encroachment regime shifts. Paper 4 reveals that all interviewed land users perceived woody encroachment to be increasing in the area. Community members and private game reserve managers mostly reported negative impacts of woody encroachment, with mixed reports from the state reserve managers. This paper also showed that private reserve managers are the most active in undertaking actions to counter encroachment.

This research can inform policy and management practices. The dissertation emphasises the importance of understanding the social and ecological interactions that underlie woody encroachment, including the worldviews of land users and managers. With the looming impacts of global warming, and possible technological advances that can change how people live and view the systems in which they live, it is important for SES managers to adopt a complex adaptive systems approach that considers possible feedbacks, drivers at local to global scales, approaching system thresholds, livelihood impacts, as well as the potential for novel planetary conditions.

Keywords: *Resilience; woody encroachment; remote sensing; social-ecological systems; ecosystem services; human well-being; savanna*

Opsomming

Die mensdom het groot sukses behaal in die verandering van die planeet om aan die eise van 'n vinnig groeiende menslike bevolking te voldoen. Aangesien menslike aktiwiteite in omvang gegroei het, het hul toenemend met die ekosisteem dinamika verband gehou, en sosiaal-ekologiese stelsels (SES) geskep. Verhoogde menslike impak op ekosisteme lei ook tot 'n verhoogde voorkoms van regime verskuiwings: groot, volgehoue veranderinge in die struktuur en funksie van ekosisteme en SES wat dikwels substantiewe impak het op 'n reeks van ekosisteemdienste wat deur hierdie stelsels voorsien word, asook op die welstand van mense wat daarin woon. Soos wêreldwye veranderinge versnel, word die beter begrip vand die druiwers van impakte en risiko's van regime verskuiwings 'n belangrike behoefte. Hierdie kennis het belangrike implikasies vir die formulering van bestuurstrategieë wat daarop gemik is om bestaande gewenste regimes te handhaaf, vorige regimes te herstel waar 'n regime verskuiwing plaasgevind het, of transformasie aan nuwe regimes in die nuwe planetêre toestande wat ons in die gesig staar te fasiliteer.

'n Gewilde regime verskuiwing in savannas wêreldwyd is bos indringing. Bos indringing is 'n verskuiwing van 'n gras savanne na 'n aanhoudende bosagtige savanne en het direkte implikasies vir 'n verskeidenheid ekosisteemdienste soos veeboerdery, en mense se lewensbestaan wat afhanklik is van hierdie dienste. Baie van die bestaande werk op bos indringing fokus op die direkte bestuurders van die proses, soos die rol van vuur of weiding om inbreuk te inhibeer of te bevorder. Minder word egter verstaan oor hoe onderliggende maatskaplike prosesse hierdie bestuurders kan beïnvloed, hoe ekologiese veranderinge terugvoering kan hê om sommige van hierdie onderliggende sosiale prosesse te beïnvloed, hoe om bos indringing as 'n skuifbeweging te monitor en hoe inbreuk op ekosisteemdienste en menslike welsyn impakteer.

Hierdie dissertasie bestaan uit vier hoofstukke in joernaal formaat. Die eerste is 'n sintese van die ekologiese druiwers en die sosiale prosesse en druiwers van bos indringing gebaseer op die gepubliseerde literatuur, geskep met behulp van oorsaaklike lusdiagramme en 'n gepubliseerde regime verskuiwing analatiese raamwerk. Die res van die hoofstukke fokus op bos indringing in die Hlabisa-distrik van Suid-Afrika. In die tweede hooftuk word Landsat TM-beelde gebruik

om die omvang van bos indringing van 1990 tot 2016 onder kontrasterende grondgebruike te kwantifiseer, spesifiek bewaringsgrond en gemeenskaplike grond wat hoofsaaklik gebruik word vir bestaansboerdery. Die derde hoofstuk bou op hoofstuk 2 en gebruik ruimtelike outokorrelasie en die opeenvolgende t-toetse-analise vir regime-verskuiwings (STARS) om te ondersoek of die veranderinge wat waargeneem word in die afstandwaarnemingsdata ooreenstem met die statistiese eienskappe van 'n regime verskuiwing. In die vierde hoofstuk was semi-gestruktureerde onderhoude gebruik om te ondersoek hoe verskillende grondgebruikers in die Hlabisa-gebied (staatsbehoudreservaat, privaat wildreservate en plaaslike gemeenskappe) deur bos indringing geraak word.

Hoofstuk 1 bied 'n breër sosiale-ekologiese begrip van bos indringing. Hierdie oorsig beklemtoon die verband tussen verhoogde menslike bevolkings (plaaslik en globaal) en bos indringing en stel sleutel bestuurs opsies voor wat gebaseer is op die belangrike terugvoerlusse wat geïdentifiseer is. In hooftuk 2 en 3 word die waarde van multi-temporale afstandwaarnemingsdata om die omvang van bos indringing te monitor en die insameling van tydreeksdata vir die opsporing van regime verskuiwings en vroeë waarskuwings tekens van hierdie verskuifings beklemtoom. In hoofstuk 2 is bevind dat Hlabisa tussen 1990 en 2016 beduidende toenames in boombedekking ondervind het, onder beide die bewaring en gemeenskaplike grondgebruike, wat daarop dui dat die veranderinge hoofsaaklik deur globale druiwers gedryf kan word eerder as plaaslike grondgebruikspraktyke. Hoofstuk 3 toon dat hierdie bos indringing 'n regime-verskuiwing was, soos bevestig deur die resultate van STARS en ruimtelike outokorrelasie. Hierdie hoofstuk dui ook daarop dat hierdie benaderings 'n metode bied wat gebruik kan word om bos indringing regime verskuiwings te monitor. Hoofstuk 4 toon aan dat alle ondervraagde landgebruikers waargeneem het dat bos indringing in die gebied verhoog het. Gemeenskapslede en private wildreservaatbestuurders het meestal negatiewe impakte van bos indringing gerapporteer, met gemengde verslae van die staats reservaat bestuurders. In hierdie hoofstuk word ook getoon dat private reserwe bestuurders die mees aktiewe is om aksies te onderneem om indringing teen te gaan.

Hierdie navorsing kan beleids- en bestuurspraktyke inlig. Die hoofstuk beklemtoon die belangrikheid van begrip van die sosiale en ekologiese interaksies wat onderliggend in bos indringing is, insluitend die wêreld menings van grondgebruikers en bestuurders. Met die dreigende impak van aardverwarming en moontlike tegnologiese vooruitgang wat kan verander hoe mense leef en die stelsels waarin hulle woon, is dit belangrik vir SES-bestuurders om 'n komplekse aanpasbare stelselsbenadering aan te neem wat moontlike terugvoerings,druiwers

op plaaslike tot globale skale, naderende stelsel drempels, lewensgevolge impak, sowel as die potensiaal vir nuwe planetêre toestande in ag te neem .

Sleutelwoorde: Veerkragtigheid; bos indringing; afstandswaarneming; sosiale-ekologiese stelsels; ekosisteemdienste; menslike welsyn; savanna

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It is surreal to be sitting here writing this part of the thesis…the final piece to add before I share it with the world. It has been a testing journey that has made me face the depths of who I am and what I am capable of withstanding. I set out to find out what makes savannas resilient to regime shifts and got to found out what makes me resilient. The answer is Love. I am so grateful for all the help and support from those I have met along this journey and those who have been there from the beginning.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Humanity has been very successful in modifying the planet to meet the demands of a rapidly growing human population (Foley *et al.*, 2005; Millennium Ecosystem Assessment, 2005). For instance, 38% of the earth's surface has been converted to agriculture (Foley *et al.*, 2011). Changes made to the environment to meet the demands of the World's growing population have led to significant improvements in human well-being (Millennium Ecosystem Assessment, 2005). However, the gains achieved by this reengineering of the planet have not been without costs, and it is now widely apparent that humanity's use of the biosphere is on an unsustainable trajectory (Foley *et al.*, 2005; Millennium Ecosystem Assessment, 2005; Rockström *et al.*, 2009; Steffen *et al.*, 2011).

Global warming is the most notorious environmental threat, but it is just one of the many aspects of global environmental change that pose significant challenges to people. For example, billions of people face problems of water scarcity and poor water quality due to degradation of ecosystems such as wetlands which play a role in providing these ecosystem services (Steffen *et al.*, 2004; Millennium Ecosystem Assessment, 2005). It has become apparent that if we do not use resources more sustainably and apply more appropriate management actions to our ecosystems, degradation will continue, hindering the ability of ecosystems to provide vital services, such as freshwater and food, that humanity depends on (Rockström *et al.*, 2009; Steffen *et al.*, 2011, 2015).

As human activities have grown in magnitude, they have become increasingly interlinked with ecosystem dynamics, creating social-ecological systems (Berkes, Folke and Colding, 1998; Gunderson and Holling, 2001; Steffen *et al.*, 2004). Social-ecological systems are complex adaptive systems that have the capacity to self-organize and adapt based on past experience (Levin, 1998, 2005; Walker *et al.*, 2004). They are characterized by emergent and nonlinear behaviour, and substantial and sometimes irreducible uncertainties (Biggs, Schlüter and Schoon, 2015). In the past, ecosystem behaviour was thought to be typified by stable equilibriums where changes to ecosystems led to gradual, predictable and reversible effects (Steffen *et al.*, 2004). This is however not always the case, as remarkably abrupt changes have occurred in nature after relatively small changes have pushed systems across a threshold leading to large changes in ecosystem structure and function (Scheffer *et al.*, 2001). Such changes are known as regime shifts. As the interconnectedness of ecosystems and social systems increases, regime shifts have been occurring more frequently and on larger scales (Lenton *et al.*, 2008; Crépin *et al.*, 2012; Levin *et al.*, 2012).

A large number of regime shifts have been documented globally, including lake eutrophication, shifts to algae-dominated coral reefs, and woody encroachment (Scheffer *et al.*, 2001; Carpenter, 2003; Troell *et al.*, 2005; Stevens, Lehmann, *et al.*, 2017). Regime shifts are widely regarded as undesirable as they often have considerable impacts on human well-being, and are costly and often impossible to reverse (Scheffer and Carpenter, 2003; Folke *et al.*, 2004; Reinette Biggs, Carpenter and Brock, 2009; Crépin *et al.*, 2012). There is substantial concern as the frequency of these shifts is increasing at the same time as the recognition of the importance of ecosystems in the provision of ecosystem services that support human well-being (Foley *et al.*, 2005; Bennett, Peterson and Gordon, 2009; Reinette Biggs, Carpenter and Brock, 2009).

Considering the magnitude of ongoing environmental changes, there is urgent need to better understand the dynamics of ecosystems and drivers of regime shifts in order to improve the management and resilience of ecosystems. This dissertation focuses on the example of woody encroachment in South Africa, to investigate how social and ecological drivers interact to create regime shifts, what the impacts are on ecosystem services and human well-being, and how regime shifts could be better mapped and monitored to inform policy that builds resilience to regime shifts.

1.2 Regime Shifts and Resilience

Regime shifts are defined as large, persistent changes in the structure and function of social-ecological systems, with substantive impacts on the suite of ecosystem services provided by these systems (Folke *et al.*, 2004; Biggs *et al.*, 2012). A regime is a range of different states in which a system maintains the same key structures and functions (Figure 1.1). System state refers to the condition of a system at a particular time and place. Alternate regimes are also sometimes referred to as alternate stable states, but here we use the word regime to differentiate more clearly between alternate system configuration (regimes) and a specific system state at a particular time.

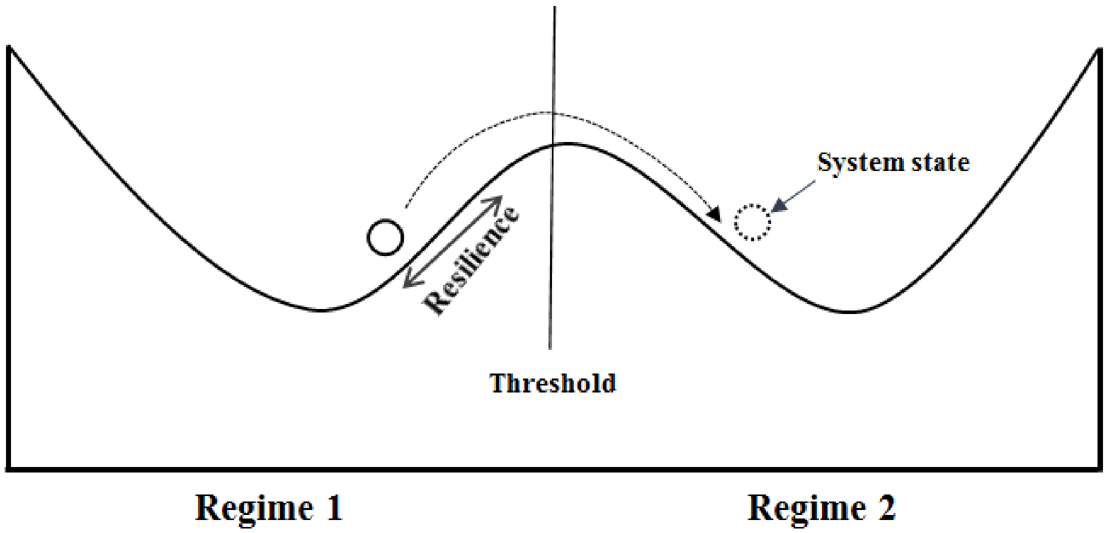

Figure 1.1: Regimes represented by a stability landscape diagram. *The valleys (or basin of attractions) represent different regimes and the peak the threshold. A regime shift occurs when the current system state (represented by the ball) shifts from one basin of attraction to another.*

Different regimes are often metaphorically represented by a cup and ball diagram (Figure 1.1). The cup represents the regime and the ball represents a system state at a particular point in time. A regime shift occurs when a system's capacity to absorb disturbance and keep operating in the same way has been eroded. Resilience can be defined as the degree to which a system is capable of absorbing disturbance and reorganizing while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Folke *et al.*, 2004; Walker *et al.*, 2004; Biggs, Schlüter and Schoon, 2015) – i.e., to withstand a regime shift (Holling 1973). Resilience therefore metaphorically refers to the size of the cup – both its depth and width. If it is shallow a small shock can cause the regime shift, while a deeper cup/system would be able to withstand a regime shift (Scheffer et al. 2001). Loss of resilience therefore makes a system vulnerable to regime shifts. As human activities such as pollution, land use change and altered fire cycles increase, so have many regime shifts as a consequence of human activities eroding the resilience of social-ecosystems (Scheffer *et al.*, 2001; Folke *et al.*, 2004; Biggs, Schlüter and Schoon, 2015).

Different regimes are created by multiple systems interactions and feedbacks that cause the system to self-organize in one of several qualitatively different configurations or regimes (Be Beisner, Haydon and Cuddington, 2003; Biggs *et al.*, 2012). Feedbacks occur when a particular change in a social-ecological system leads to further changes that eventually loop back to affect the original variable (Meadows, 2003). Feedbacks can either be balancing or reinforcing (Figure 1.2). Balancing feedback loops are equilibrating structures in a system, that are both sources of stability and sources of resistance to change (Meadows, 2003; Biggs *et al.*, 2012). Reinforcing feedback loops are amplifying, positive, and self-multiplying structures in a system that can cause healthy growth or a runaway collapse over time (Meadows, 2003; Biggs *et al.*, 2012).

Most systems have both types of feedback loops: reinforcing loops that drive change and at least one balancing loop that constrains change. In a system where one loop dominates others, that loop will have a stronger impact on the system's state (Meadows, 2003). Dominance is an important concept in systems because most systems have several competing feedback loops operating simultaneously; those loops that dominate the system will determine the system's regime and subsequently a system's state (Meadows, 2003). Most ecosystems are complex and have multiple feedbacks loops with multiple possible regimes separated by an unstable equilibrium that marks the border between the regimes or basins of attraction (Scheffer *et al.*, 2001).

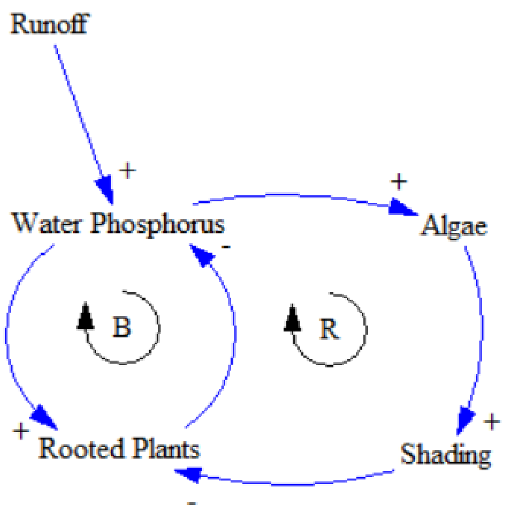

Figure 1.2: A simplified diagram illustrating feedback loops in a lake system. *An increase of phosphorous in the water has two effects. It enhances the growth of the rooted plants which use and thereby decrease the amount of phosphorous in the water, creating a balancing feedback (B). Increased phosphorous also increases the amount of algae in water which shades the rooted plants preventing their growth and therefore the uptake of phosphorous, creating a reinforcing feedback (R). A regime shift occurs when the reinforcing feedback loop becomes dominant, eventually leading to the death of the rooted plants.*

Regime shifts occur for two main reasons: as a result of gradual change, slowly weakening the dominant system feedbacks that maintain a regime, or from an external shock (Folke et al. 2004; Crépin et al. 2012; Biggs et al. 2012; Figure 1.3). An example of a gradual change in a system potentially causing a regime shift is the gradual decrease in the amount of water in herbaceous wetlands, as less water is unfavourable to herbaceous hydrophytes but favourable to invasive tree species. These invasives can tolerate moderate flooding, and gain a competitive edge over the hydrophytes, leading to tree invasion and the formation of woodlands (Luvuno, Kotze and Kirkman, 2016). An example of an external shock causing a regime shift is when a disease wipes out the top predator in a food web, changing the structure of the food web so that the prey becomes substantially more abundant due to the lack of a predator (Scheffer et al., 2001; Carpenter, 2003).

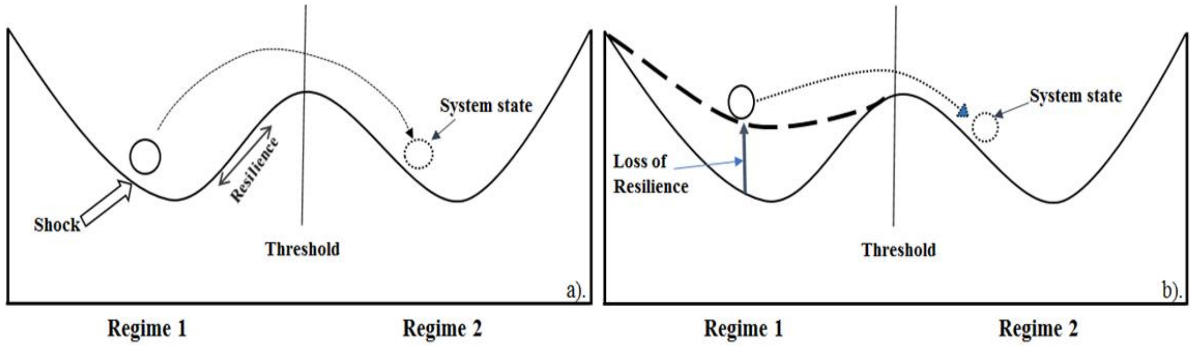

Figure 1.3: Illustration of regime shifts. *a). Shock pushes the system past the threshold from regime 1 into regime 2. b). A slow variable leads to a gradual loss of resilience and causes regime 1 to disappear. Modified from Biggs et al. (2012).*

Most often regime shifts result from a combination of ongoing gradual changes and a large shock to the system. Slow changes may gradually weaken the dominant feedbacks with no visible system change until an external shock hits the system, causing it to cross a critical threshold and shift into an alternate regime (Scheffer *et al.*, 2009; Biggs *et al.*, 2012; Crépin *et al.*, 2012). Regime shifts can also occur when a reinforcing feedback loop switches direction. This happens when the condition of a variable changes and causes the same feedback to reinforce a different regime.

Regime shifts tend to occur where slow driving variables are at an intermediate level (Andersen *et al.*, 2009). In the wetland example above, this would be in situations where the wetland is neither permanently or semi-permanently flooded – i.e. when the conditions and feedbacks can favour either regime. The system is in an unstable state in this period. In prolonged, permanently flooded situations only hydrophytes can persist, while in long dry periods trees persist as most hydrophytes are not suited to dry conditions. Detecting when a system in these unstable situations will undergo a regime shift is challenging as a drop or rise of the water table can go undetected until the system crosses a threshold at which a different set of feedbacks become dominant, and the system moves into a different regime. This is depicted in Figure 1.3 where an increase in driver does not cause a change in the regime until a certain point where the system shifts into a different regime (Andersen *et al.*, 2009).

Reversing a regime shift requires sufficient understanding of the system to know which feedbacks are, and were, dominant and what actions can recreate loss, or break unwanted, feedback loops. The strength of the dominant feedbacks in the system determines how easy it is to reverse a specific regime shift (Meadows, 2003).

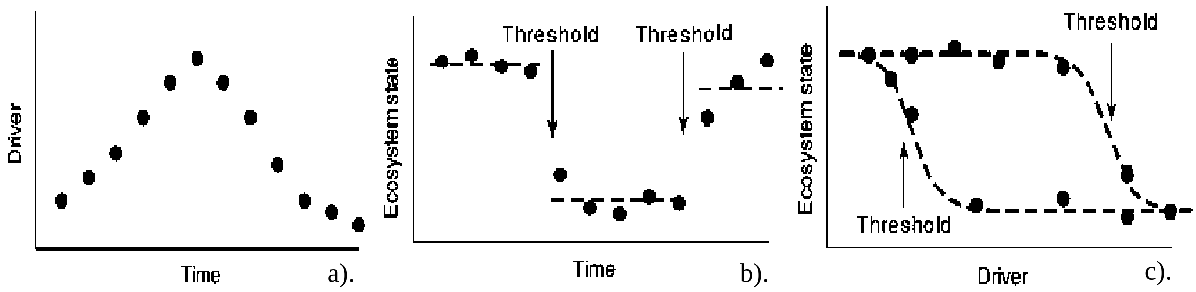

Figure 1.4: The interaction between a slow variable which drives the system and ecosystem state. *Figure 1.4a illustrates the change of a driver over time; 3b illustrates the change in ecosystem state as a result of the change in driver. Note that the dashed lines represent the regimes and the dots represent ecosystem state at time x. 3c illustrates a hysteresis effect linking the ecosystem state to the environmental driver. A jump between two alternative regimes occurs when the driver is first slowly increased and then decreased again. Note that the possibility for alternate regimes exists at intermediate levels of the driver (Andersen et al. 2009).*

1.3 WOODY ENCROACHMENT: A CASE STUDY FOR EXPLORING REGIME SHIFTS

One of the most documented regime shift that is occurring across the globe is the shift from open grassy ecosystems such as grasslands or savannas into closed canopy woodlands and forests (Luvuno et al. 2018; Rocha et al. 2018). This is termed woody encroachment, i.e. an increase in the cover of indigenous woody species in herbaceous dominated systems. Savannas and grasslands are vital ecosystems that support a range of livelihoods, economic activities and biodiversity (Gray and Bond, 2013). In Africa, these ecosystems provide food and clean water, grazing for cattle ranching, and sustain some of the country's flagship conservation areas and support biodiversity(Sankaran *et al.*, 2005; Gray and Bond, 2013). Woody encroachment therefore has significant economic, cultural and ecological implications (Wigley, Bond and Hoffman, 2009; Bond and Midgley, 2012; Gray and Bond, 2013; Shackleton *et al.*, 2013).

Woody encroachment has been a problem in southern Africa for nearly a century (O'Connor, Puttick and Hoffman, 2014). There have been many studies trying to understand woody encroachment (Knoop and Walker, 1985; Belsky and Canham, 1994; Sankaran *et al.*, 2005; Kraaij and Ward, 2006; Wiegand, Saltz and Ward, 2006; Meyer, Wiegand and Ward, 2009; Wigley, Bond and Hoffman, 2009; Buitenwerf, Bond, Stevens and Trollope, 2012; Stevens *et al.*, 2016), yet there remains much debate concerning the causes and drivers of change (Venter, Cramer and Hawkins, 2018). Proposed drivers include altered fire regimes/fire suppression (Higgins *et al.*, 2000; Sankaran *et al.*, 2005; Archibald *et al.*, 2009), rainfall and drought (Roques, O'Connor and Watkinson, 2001; Fensham, Fairfax and Archer, 2005; Kraaij and Ward, 2006), widespread elimination of megafauna (Staver and Bond, 2014; Daskin, Stalmans and Pringle, 2016; Skowno *et al.*, 2017), rising CO_2 atmospheric concentrations (Wigley, Bond and Hoffman, 2010; Buitenwerf, Bond, Stevens and Trollope, 2012; Stevens *et al.*, 2016; Nackley *et al.*, 2018) and reduced fuelwood collection (Shackleton *et al.*, 2013; Russell and Ward, 2014).

These different drivers can be encompassed in two models for understanding savanaa dynamics and the key drivers of change in these systems: demographic bottleneck models and competition-based models. Demographic-bottleneck models emphasise the impact of disturbance and water availability on woody encroachment (Sankaran, Ratnam and Hanan, 2004; O'Connor, Puttick and Hoffman, 2014). Competition-based models emphasise the competitive interaction of trees and grass, with co-existence resulting from spatial or temporal niche separation (Ward, Wiegand and Getzin, 2013; O'Connor, Puttick and Hoffman, 2014). Competitive models propose that grasses are competitively better in savannas due to shallow rooted grasses being more water-use efficient than trees which are deep rooted and rely mainly on water from deep soil layers (O'Connor, Puttick and Hoffman, 2014). Competitive models implicate overgrazing (reduction in grass cover) and fire (reduces tree cover and promotes grass cover) as important drivers of encroachment, since fire and over grazing both affect the competitive vigour of the plants (Sankaran *et al.*, 2005; Ward, 2005; Staver *et al.*, 2009).

A second, but different mechanism where fire can drive woody encroachment is that fire suppression allows trees to escape the fire trap where they remain reproductively immature (Higgins *et al.*, 2000; Bond, Midgley and Woodward, 2003; Uys, Bond and Everson, 2004; de Villiers and O'Connor, 2010; Ratajczak *et al.*, 2014). The extent of tree escape and potential canopy closure depends on the mean annual rainfall of the region and changes in rainfall patterns (Sankaran *et al.*, 2005; Skowno *et al.*, 2017). Sankaran *et al.*, (2005), based on collated data from 854 sites across Africa, concluded that water availability in areas where the MAP is less than 650 mm per year (semi-arid savannas) limits woody cover percentage, whereas in areas with a MAP of 650 mm per year and higher (mesic savannas), woody cover percentage is determined by mainly fire (Sankaran *et al.*, 2005). Similarly removal of browsers and mega-herbivores also releases trees from the browse trap (Van Langevelde *et al.*, 2003; Staver *et al.*, 2009; da Silveira Pontes *et al.*, 2012; O'Connor, Puttick and Hoffman, 2014; Staver and Bond, 2014).

Currently, rising atmospheric carbon dioxide (CO_2) and associated climatic changes are thought to be the leading driver of woody encroachment, as it promotes root growth and growth rate of saplings which allows them to escape the fire trap (Bond and Midgley, 2000, 2012; Kgope, Bond and Midgley, 2010). In arid savannas, increasing atmospheric CO_2 is thought to enhance plant water use efficiencies due to reduced stomatal conductance causing greater water filtration and increased soil water (Polley, 1997; Nackley *et al.*, 2018). There is growing empirical evidence (Kgope, Bond and Midgley, 2010; Wigley, Bond and Hoffman, 2010; Buitenwerf, Bond, Stevens and Trollope, 2012; Stevens *et al.*, 2016; Skowno *et al.*, 2017; Nackley *et al.*, 2018) suggesting that atmospheric enrichment of carbon dioxide (CO_2) is driving the widespread encroachment of woody plants into open savannas.

In a recent review of the drivers of woody encroachment O'Connor *et al.*, (2014) concluded that the occurrence of woody encroachment depends on the interplay of all the aforementioned drivers and recognition of this is essential for containing encroachment. If woody encroachment is likely increasing with increased atmospheric CO_2, managers of these SES systems likely need to adapt their management strategies in order to contain encroachment.

1.4 ECOSYSTEM SERVICES AND HUMAN WELL-BEING IMPACTS

Regime shifts often lead to abrupt shifts in ecosystem services that have significant impacts on societies (Walker *et al.*, 2004; Bennett, Peterson and Gordon, 2009; Biggs, Schlüter and Schoon, 2015). Ecosystem services are the goods and services which ecosystems provide that contribute to making human life both possible and worth living (Costanza *et al.*, 1997; Díaz *et al.*, 2006; Cardinale *et al.*, 2012). Ecosystem services range from the direct provision of goods (e.g. food, timber and medicines) to regulatory services (functioning of ecosystem processes e.g. soil formation, nutrient cycling, water retention) and are often associated directly with the presence of particular species of plants and animals (Chapin *et al.*, 2000; Loreau *et al.*, 2001; Diaz *et al.*, 2004; Cardinale *et al.*, 2012). Ecosystem changes typically entail changes in biodiversity, and can result in the ecosystem effectively not supplying some ecosystem goods and services or suppling them to a lesser degree (Troell *et al.*, 2005). These changes in ecosystem services and their flows can affect livelihoods, income, local migration and, political conflict (Arico *et al.*, 2005). The impacts of regime shifts on economic and physical security, freedom, choice and social relations therefore have wide-ranging impacts on human well-being (Arico *et al.*, 2005; Millennium Ecosystem Assessment, 2005).

50% of the world's livestock farming takes place in open grassy savannas, which cover around 20% of the earth's terrestrial surface (Chapin *et al.*, 2000; Archer, Boutton and Mcmurtry, 2004). These systems are particularly important as rangelands for cattle and wildlife ranching (Sankaran, Ratnam and Hanan, 2004). Woody encroachment brings a relatively rapid change where over a decade or two, a highly productive grass layer can be lost (Anderies, Janssen and Walker, 2002; Scholes, 2003). This substantially reduces the grazing capacity of the land (Roques, O'Connor and Watkinson, 2001) as access becomes restricted by trees, and forage is reduced with declining grass cover. This reduces the overall carrying capacity of the land (Roques, O'Connor and Watkinson, 2001; Anadón *et al.*, 2014) with major impacts on cattle ranchers. For example, in Namibia, cattle numbers were reduced by ~64% from 1959 to 2004 due to woody encroachment, with an estimated loss of more than N$700 million (1US$ ~ 14.45N$) per annum (Gray and Bond, 2013). Changes in woody cover and carrying capacity are not proportional, as small increases in tree cover can result in marked reductions in livestock production (Eldridge *et al.*, 2011; Anadón *et al.*, 2014). Woody encroachment therefore directly impacts the farmers and their livelihoods, as well as regional and national economies.

Furthermore, people with rural livelihoods often rely on wild plants as a buffer against poverty. Wild plants can be used for consumption, medicine, construction, cultural and spiritual rituals and sale (Wyk, 2002; Cocks and Dold, 2008; Tefera, Dlamini and Dlamini, 2008; Comberti *et al.*, 2015; Ryan *et al.*, 2016). Encroachment can negatively affect abundance and access to such plants. Alternatively, in areas where multi-species encroachment has occurred, benefits may be experienced in goat ranching, access to firewood and medicinal plants (Tefera, Dlamini and Dlamini, 2008; Wigley, Bond and Hoffman, 2009). This contrasts with research in areas where a single tree species was the main encroacher, and the rural community had negative attitudes towards increased tree density linked to anxiety about wild animals harming their crops, loss of arable land and loss of landscape identity (Shackleton *et al.*, 2013).

In Africa, savannas are home to most of the world's remaining megaherbivores, which are an important attraction for tourism (Gray and Bond, 2013). The tourism industry in South Africa employs 4.5% of the population and in 2015 contributed 3.1% to the South African gross domestic product (StatsSA). An African safari experience is an important component of tourist attraction to Africa (Buckley *et al.*, 2012). Encroachment impacts negatively on tourism by impairing visibility and reducing game viewing opportunities, as well as by changing the biodiversity of the area, e.g. cheetahs, wildebeest, white rhino and certain bird species need open areas to thrive (Maciejewski and Kerley, 2014).

Shifts from grassy to woody savannas have also been found to negatively impact the quantity and quality of water supplies, soil health, carbon sequestration, and the maintenance of biodiversity (Briggs *et al.*, 2005; Huxman *et al.*, 2005; Eldridge *et al.*, 2011; Archer and Predick, 2014; Honda *et al.*, 2016). These are all important regulating and supporting services. Changes in these services are likely to compromise human well-being in the future, as provisioning services cannot continue to increase if the supporting and regulating services are degraded (Raudsepp-Hearne *et al.*, 2010).

1.5 Research aim

The overall aim of my PhD was to better understand social-ecological regime shifts, their impacts and how they might be monitored and managed, by investigating the example of woody encroachment in South Africa.

This overall aim was addressed through four key research questions:

Q1. What are the ecological and social processes underlying woody encroachment, and how do they interact to drive encroachment? (Chapter 2)

Q2. Can we use readily available remotely sensed data to assess and monitor encroachment across different land uses? (Chapter 3)

Q3. Does woody encroachment conform to the statistical properties of a regime shift, and can we use these properties to monitor woody encroachment regime shifts? (Chapter 4)

Q4. How are stakeholders associated with different land uses impacted by woody encroachment? (Chapter 5)

1.6 Study Area Description

The study was undertaken in the Hlabisa district area of KwaZulu-Natal, South Africa (28.00°S to 28.25°S and 32.00°E to 32.58°E; Figure 1.5). This region has been identified as one of the most heavily encroached regions in South Africa (Skowno *et al.*, 2017) and historical aerial photography from nearby areas indicate that this region is in the process of changing from an open grassland to a heavily wooded thicket (Wigley, Bond and Hoffman, 2009).

The mean annual precipitation (MAP) of the Hlabisa district ranges from 700 mm - 990 mm per annum, with most of the rainfall falling in the summer months of September to March (Wigley, Bond and Hoffman, 2010). Temperatures in the area are warm to hot, particularly during the summer months. Mean annual temperature in the region is 22.5 °C with a mean minimum July temperature of 13 °C and a mean maximum February temperature of 35 °C (Wigley, Bond and Hoffman, 2010). The study area falls predominantly into Northern Zululand Sourveld (SVI 22) with some Zululand Lowveld (SVI 23) and patches of Scarp Forest (FOz5) (Mucina and Rutherford, 2006). Soils are mainly derived from Karoo sediments (shales, mudstones, sandstones) interspersed with dolerite intrusions producing clay-rich soils (Wigley, Bond and Hoffman, 2009).

Land use in the area comprises of the conservation areas, communal lands and commercial farms. The communal lands and commercial farming in this area started in the early 1900s, with cattle farming being the predominant land-use practice. From the 1970s, many of the commercial farmers in the area changed from cattle farming to game farming (Wigley, Bond and Hoffman, 2009). Communal lands are areas that have been utilized by rural communities, mostly comprise small scale subsistence farming, for over centuries (Marks, 1967; Chanaiwa, 1980), and still operate under traditional tenure arrangements (Higgins, Shackleton and Robinson, 1999).

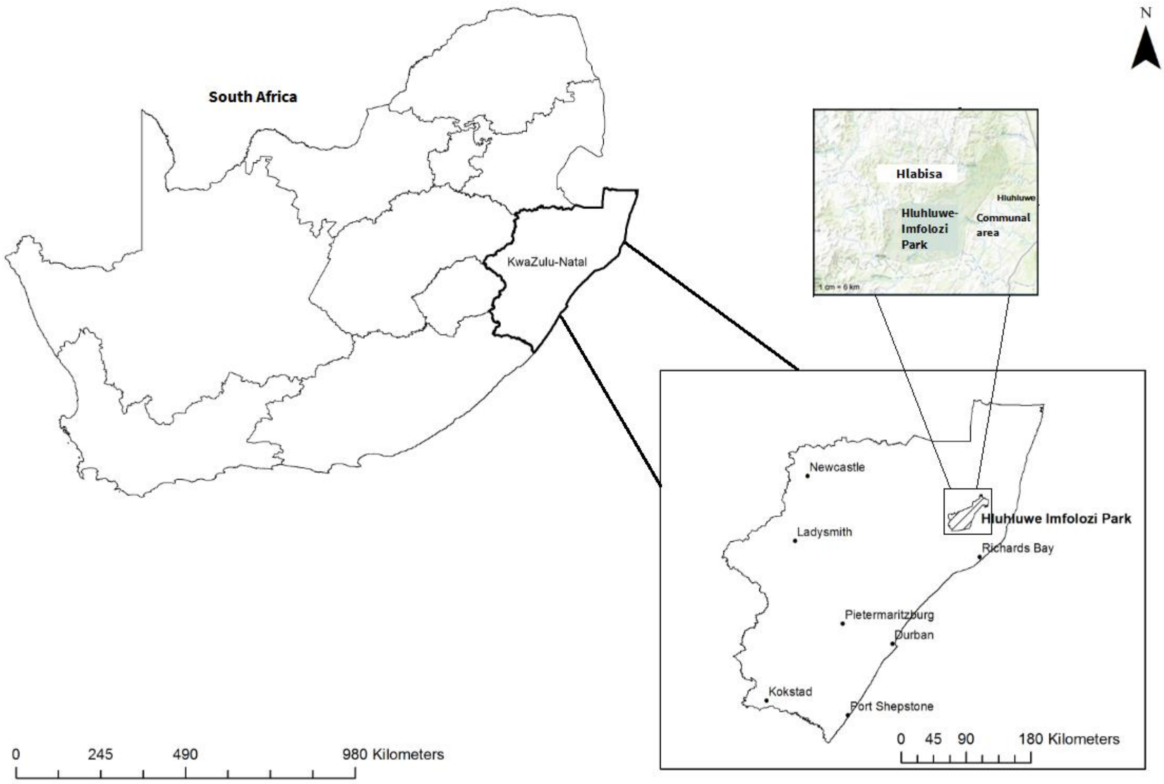

Figure 1.5: Study site location: the Hlabisa district in Zululand.

1.7 STRUCTURE AND OVERVIEW

The dissertation consists of six chapters, four of which are in the format of journal articles. Chapter 2 has already been published in Sustainability, a peer reviewed international scientific journal, and the rest are in preparation for submission. This first chapter introduces the reader to the challenges the research seeks to address, as well as outline the aim and objectives of the research. The remainder of the dissertation comprises the following:

Chapter 2 aims to review woody encroachment in African savannas using a social-ecological regime shift lens. This chapter focuses on identifying the key drivers, and feedbacks using the Regime Shifts Database Framework (Biggs *et al.* 2018). Specifically, this chapter examines the ecological and social processes underlying encroachment and how changes in these processes weaken, strengthen or alter social and ecological feedbacks in arid and mesic savannas.

Chapter 3 presents results of a time series analysis using Landsat TM imagery to identify and quantify woody encroachment from 1990 to 2016 in Hlabisa, South Africa. This area consists of contrasting land use practices which helps to illustrate the potential links between the effect of local (management practices) and global drivers in the process of woody encroachment. The aim of this chapter is to test an approach to large-scale mapping and quantify woody encroachment across different land uses, and therefore management strategies.

Chapter 4 builds on the results reported in Chapter 3. The Landsat data are used to test if the changes observed in Chapter 3 conform to the statistical properties of a regime shift. There have been a number of proposed early warning indicators for ecological transitions that occur prior to system undergoing a regime shift. This chapter uses changes in variance, autocorrelation and sequential t-tests to assess regime shifts in the Hlabisa area.

Chapter 5 focused on the impact of woody encroachment on local land users and their livelihoods, and how this in turn influences their ecosystem management strategies. This chapter used semi-structured questionnaires to investigate how rural communities and game reserve managers perceive woody encroachment, how it impacts them, and what the costs of reversing woody encroachment are.

Chapter 6 provides a synthesis of this dissertation, and the implications for research and practice. This chapter also reflects on the limitations of the study, and future research directions.

1.8 References

Anadón, José D, Osvaldo E. Sala, B. L. Turner, Elena M. Bennett, J. D. Anadon, Osvaldo E. Sala, B. L. Turner, and Elena M. Bennett. 2014. "Effect of Woody-Plant Encroachment on Livestock Production in North and South America." *Proceedings of the National Academy of Sciences of the United States of America* 111 (35): 12948–53. https://doi.org/10.1073/pnas.1320585111.

Anderies, John M., Marco A. Janssen, and Brian H. Walker. 2002. "Grazing Management, Resilience, and the Dynamics of a Fire-Driven Rangeland System." *Ecosystems* 5 (1): 23–44. https://doi.org/10.1007/s10021-001-0053-9.

Andersen, Tom, Jacob Carstensen, Emilio Hernández-García, and Carlos M Duarte. 2009. "Ecological Thresholds and Regime Shifts: Approaches to Identification." *Trends in Ecology & Evolution* 24 (1): 49–57. https://doi.org/10.1016/j.tree.2008.07.014.

Archer, Steve, Thomas W Boutton, and Chad R Mcmurtry. 2004. "Carbon and Nitrogen Accumulation in a Savanna Landscape: Field and Modeling Perspectives." In *Global Environmental Change in the Ocean and on Land*, edited by Masae Shiyomi, Hodaka Kawahata, Hiroshi Koizumi, Atsushi Tsuda, and Yoshio Awaya, 359–73. Tokyo: Terrapub.

Archer, Steven R., and Katharine I. Predick. 2014. "An Ecosystem Services Perspective on Brush Management: Research Priorities for Competing Land-Use Objectives." Edited by Fernando Maestre. *Journal of Ecology* 102 (6): 1394–1407. https://doi.org/10.1111/1365-2745.12314.

Archibald, Sally, David P. Roy, Brian W. van Wilgen, and Robert J. Scholes. 2009. "What Limits Fire? An Examination of Drivers of Burnt Area in Southern Africa." *Global Change Biology* 15: 613–30. https://doi.org/10.1111/j.1365-2486.2008.01754.x.

Arico, Salvatore, Peter Bridgewater, Adel El-beltagy, Erika Harms, Senior Program, Robert Hepworth, Kerstin Leitner, et al. 2005. "Ecosystems AND HUMAN WELL-BEING." Edited by Robert T Watson, Thomas Rosswall, Achim Steiner, Klaus Töpfer, Salvatore Arico, and Peter Bridgewater. *Ecosystems*, Millenium Assessments, 5 (281): 1–100. https://doi.org/10.1196/annals.1439.003.

Beisner, Be, Dt Haydon, and K. Cuddington. 2003. "Alternative Stable States in Ecology." *Frontiers in Ecology and the Environment* 1 (7): 376–82. https://doi.org/10.1890/1540-9295(2003)001[0376:ASSIE]2.0.CO;2.

Belsky, A. Joy, and Charles D. Canham. 1994. "Forest Gaps and Isolated Savanna Trees." *BioScience* 44 (2): 77–84. https://doi.org/10.2307/1312205.

Bennett, Elena M., Garry D. Peterson, and Line J. Gordon. 2009. "Understanding Relationships among Multiple Ecosystem Services." *Ecology Letters* 12 (12): 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x.

Berkes, Fikret., Carl. Folke, and Johan. Colding. 1998. *Linking Social and Ecological Systems : Management Practices and Social Mechanisms for Building Resilience*. Cambridge University Press.

Biggs, Reinette, Thorsten Blenckner, Carl Folke, Line Gordon, Albert Norström, Magnus Nyström, and Garry Peterson. 2012. "Regime Shifts." In *Encyclopedia of Theoretical Ecology*, edited by L Hastings, A; Gross, 609–17. Ewing, NJ, USA: University of

California Press.

Biggs, Reinette, Stephen R Carpenter, and William a Brock. 2009. “Turning Back from the Brink: Detecting an Impending Regime Shift in Time to Avert It.” *Proceedings of the National Academy of Sciences of the United States of America* 106 (3): 826–31. https://doi.org/10.1073/pnas.0811729106.

Biggs, Reinette, Maja Schlüter, and Michael L. Schoon. 2015. *Principles for Building Resilience : Sustaining Ecosystem Services in Social-Ecological Systems*. Edited by Reinette Biggs, Maja Schlüter, and Michael L. Schoon. Cambridge: Cambridge University Press.

Bond, W. J., G. F. Midgley, and F. I. Woodward. 2003. “The Importance of Low Atmospheric CO2 and Fire in Promoting the Spread of Grasslands and Savannas.” *Global Change Biology* 9: 973–82. https://doi.org/10.1046/j.1365-2486.2003.00577.x.

Bond, William J, and Guy F. Midgley. 2000. “A Proposed CO 2 -Controlled Mechanism of Woody Plant Invasion in Grasslands and Savannas.” *Global Change Biology* 6: 865–69. https://doi.org/10.1046/j.1365-2486.2000.00365.x.

Bond, William J, and Guy F Midgley. 2012. “Carbon Dioxide and the Uneasy Interactions of Trees and Savannah Grasses.” *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 367 (1588): 601–12. https://doi.org/10.1098/rstb.2011.0182.

Briggs, John M., ALAN K. Knapp, JOHN M. Blair, JANA L. Heisler, GREG A. Hoch, MICHELLE S. Lett, James K. McCARRON, et al. 2005. “An Ecosystem in Transition: Causes and Consequences of the Conversion of Mesic Grassland to Shrubland.” *BioScience* 55 (3): 243. https://doi.org/10.1641/0006-3568(2005)055[0243:AEITCA]2.0.CO;2.

Buckley, Ralf C, J Guy Castley, Fernanda De Vasconcellos, Alexa C Mossaz, and Rochelle Steven. 2012. “A Population Accounting Approach to Assess Tourism Contributions to Conservation of IUCN-Redlisted Mammal Species.” https://doi.org/10.1371/journal.pone.0044134.

Buitenwerf, R., W. J. Bond, N. Stevens, and W. S. W. Trollope. 2012a. “Increased Tree Densities in South African Savannas: >50 Years of Data Suggests CO2 as a Driver.” *Global Change Biology* 18 (2): 675–84. https://doi.org/10.1111/j.1365-2486.2011.02561.x.

Buitenwerf, R., W. J. Bond, N. Stevens, and W. S W Trollope. 2012b. “Increased Tree Densities in South African Savannas: >50 Years of Data Suggests CO 2 as a Driver.” *Global Change Biology* 18 (2): 675–84. https://doi.org/10.1111/j.1365-2486.2011.02561.x.

Cardinale, Bradley J, J Emmett Duffy, Andrew Gonzalez, David U Hooper, Charles Perrings, Patrick Venail, Anita Narwani, et al. 2012. “Biodiversity Loss and Its Impact on Humanity.” *Nature* 486 (7401): 59–67. https://doi.org/10.1038/nature11148.

Carpenter, S. 2003. *Regime Shifts in Lake Ecosystems:Pattern and Variation: 15 Excellence in Ecology: Amazon.Co.Uk: Stephen R Carpenter, Otto Kinne: Books*. Edited by O Kinne. Oldendorf: International Ecology Institute. https://www.amazon.co.uk/Regime-Shifts-Lake-Ecosystems-Excellence/dp/3946729150.

Chanaiwa, David Shingirai. 1980. "The Zulu Revolution: State Formation in a Pastoralist Society." *African Studies Review* 23 (3): 1. https://doi.org/10.2307/523668.

Chapin III, F. Stuart, Erika S. Zavaleta, Valerie T. Eviner, Rosamond L. Naylor, Peter M. Vitousek, Heather L. Reynolds, David U. Hooper, et al. 2000. "Consequences of Changing Biodiversity." *Nature* 405 (6783): 234–42. https://doi.org/10.1038/35012241.

Cocks, M L, and A P Dold. 2008. "The Cultural Use of the Wild Olive Tree by the AmaXhosa People in the Eastern Cape Province of South Africa." *JSRNC* 3: 292–308. https://doi.org/10.1558/jsrnc.v2i3.292.

Comberti, C., T.F. Thornton, V. Wyllie de Echeverria, and T. Patterson. 2015. "Ecosystem Services or Services to Ecosystems? Valuing Cultivation and Reciprocal Relationships between Humans and Ecosystems." *Global Environmental Change* 34: 247–62. https://doi.org/10.1016/j.gloenvcha.2015.07.007.

Costanza, Robert, Ralph d'Arge, Rudolf de Groot, Stephen Farber, Monica Grasso, Bruce Hannon, Karin Limburg, et al. 1997. "The Value of the World's Ecosystem Services and Natural Capital." *Nature*. https://doi.org/10.1038/387253a0.

Crépin, Anne-Sophie, Reinette Biggs, Stephen Polasky, Max Troell, and Aart de Zeeuw. 2012. "Regime Shifts and Management." *Ecological Economics* 84: 15–22. https://doi.org/10.1016/j.ecolecon.2012.09.003.

Daskin, Joshua H., Marc Stalmans, and Robert M. Pringle. 2016. "Ecological Legacies of Civil War: 35-Year Increase in Savanna Tree Cover Following Wholesale Large-Mammal Declines." Edited by Lorena Gomez-Aparicio. *Journal of Ecology* 104 (1): 79–89. https://doi.org/10.1111/1365-2745.12483.

Díaz, Sandra, Joseph Fargione, F Stuart Chapin, and David Tilman. 2006. "Biodiversity Loss Threatens Human Well-Being." *PLoS Biology* 4 (8): e277. https://doi.org/10.1371/journal.pbio.0040277.

Diaz, Sandra, J.G. G Hodgson, K. Thompson, Marcelo Cabido, J.H.C. Johannes H C Cornelissen, A. Jalili, G. Montserrat-Martí, et al. 2004. "The Plant Traits That Drive Ecosystems: Evidence from Three Continents." *Journal of Vegetation Science* 15 (3): 295–304. https://doi.org/10.1658/1100-9233(2004)015[0295:TPTTDE]2.0.CO;2.

Eldridge, David J, Matthew A Bowker, Fernando T Maestre, Erin Roger, James F Reynolds, and Walter G Whitford. 2011. "Impacts of Shrub Encroachment on Ecosystem Structure and Functioning: Towards a Global Synthesis." *Ecology Letters* 14 (7): 709–22. https://doi.org/10.1111/j.1461-0248.2011.01630.x.

Fensham, R. J., R. J. Fairfax, and S. R. Archer. 2005. "Rainfall, Land Use and Woody Vegetation Cover Change in Semi-Arid Australian Savanna." *Journal of Ecology* 93 (3): 596–606. https://doi.org/10.1111/j.1365-2745.2005.00998.x.

Foley, Jonathan a., Navin Ramankutty, Kate a. Brauman, Emily S. Cassidy, James S. Gerber, Matt Johnston, Nathaniel D. Mueller, et al. 2011. "Solutions for a Cultivated Planet." *Nature* 478: 337–42. https://doi.org/10.1038/nature10452.

Foley, Jonathan a, Ruth Defries, Gregory P Asner, Carol Barford, Gordon Bonan, Stephen R Carpenter, F Stuart Chapin, et al. 2005. "Global Consequences of Land Use." *Science (New York, N.Y.)* 309 (5734): 570–74. https://doi.org/10.1126/science.1111772.

Folke, Carl, Steve Carpenter, Brian Walker, Marten Scheffer, Thomas Elmqvist, Lance

Gunderson, and C.S. Holling. 2004. “Regime Shifts, Resilience, and Biodiversity in Ecosystem Management.” *Annual Review of Ecology, Evolution, and Systematics* 35 (1): 557–81. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711.

Gray, Emma F., and William J. Bond. 2013. “Will Woody Plant Encroachment Impact the Visitor Experience and Economy of Conservation Areas?” *Koedoe* 55 (1): 1–9. https://doi.org/10.4102/koedoe.v55i1.1106.

Gunderson, Lance H., and C. S. Holling. 2001. *Panarchy : Understanding Transformations in Human and Natural Systems*. Island Press.

Higgins, Steven I, Higgins, William J Bond, and Winston S W Trollope. 2000. “Fire Resprouting and Variability a Recipe for Grass Tree Coexistence in Savanna.Pdf.” *Journal of Ecology* 88 (2): 213–29.

Higgins, Steven I, Charlie M Shackleton, and E Robbie Robinson. 1999. “Changes in Woody Community Structure and Composition under Contrasting Landuse Systems in a Semi.” *Journal of Biogeography* 26 (3): 619–27. https://www.jstor.org/stable/pdf/2656147.pdf?refreqid=excelsior%3A79b3410e731dd3505e9d58ff224af70e.

Honda, Eliane A, Giselda Durigan, DMJS. Bowman, A. Walsh, DJ. Milne, KG. Roques, TG. O’Connor, et al. 2016. “Woody Encroachment and Its Consequences on Hydrological Processes in the Savannah.” *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 371 (1703): 115–33. https://doi.org/10.1098/rstb.2015.0313.

Huxman, Travis E, Bradford P Wilcox, David D Breshears, Russell L Scott, Keirith A Snyder, Eric E Small, Kevin Hultine, William T Pockman, and Robert B Jackson. 2005. “Ecohydrological Implications of Woody Encroachment.” *Special Feature Ecology* 86 (2): 308–19.

Kgope, Barney S., William J. Bond, and Guy F. Midgley. 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: 451–63. https://doi.org/10.1111/j.1442-9993.2009.02046.x.

Knoop, W. T., and B. H. Walker. 1985. “Interactions of Woody and Herbaceous Vegetation in a Southern African Savanna.” *The Journal of Ecology* 73 (1): 235. https://doi.org/10.2307/2259780.

Kraaij, T., and D. Ward. 2006. “Effects of Rain, Nitrogen, Fire and Grazing on Tree Recruitment and Early Survival in Bush-Encroached Savanna, South Africa.” *Plant Ecology* 186 (2): 235–46. https://doi.org/10.1007/s11258-006-9125-4.

Lade, Steven J, Susa Niiranen, Jonas Hentati-Sundberg, Thorsten Blenckner, Wiebren J Boonstra, Kirill Orach, Martin F Quaas, Henrik Österblom, and Maja Schlüter. 2015. “An Empirical Model of the Baltic Sea Reveals the Importance of Social Dynamics for Ecological Regime Shifts.” *Proceedings of the National Academy of Sciences* 112 (35): 11120–25. https://doi.org/10.1073/pnas.1504954112.

Langevelde, Frank Van, Claudius A. D. M. Van De Vijver, Lalit Kumar, Johan Van De Koppel, Nico De Ridder, Jelte Van Andel, Andrew K. Skidmore, et al. 2003. “EFFECTS OF FIRE AND HERBIVORY ON THE STABILITY OF SAVANNA ECOSYSTEMS.” *Ecology* 84 (2): 337–50. https://doi.org/10.1890/0012-9658(2003)084[0337:EOFAHO]2.0.CO;2.

Lenton, Timothy M, Hermann Held, Elmar Kriegler, Jim W Hall, Wolfgang Lucht, Stefan Rahmstorf, and Hans Joachim Schellnhuber. 2008. “Tipping Elements in the Earth’s Climate System.” *Proceedings of the National Academy of Sciences of the United States of America* 105 (6): 1786–93. https://doi.org/10.1073/pnas.0705414105.

Levin, Simon A. 1998. “Ecosystems and the Biosphere as Complex Adaptive Systems.” *Ecosystems* 1 (5): 431–36. https://doi.org/10.1007/s100219900037.

Levin, Simon A. 2005. “Self-Organization and the Emergence of Complexity in Ecological Systems.” *BioScience* 55 (12): 1075. https://doi.org/10.1641/0006-3568(2005)055[1075:SATEOC]2.0.CO;2.

Levin, Simon, Tasos Xepapadeas, Anne-Sophie Crépin, Jon Norberg, Aart de Zeeuw, Carl Folke, Terry Hughes, et al. 2012. “Social-Ecological Systems as Complex Adaptive Systems: Modeling and Policy Implications.” *Environment and Development Economics* 18 (02): 111–32. https://doi.org/10.1017/S1355770X12000460.

Loreau, M, S Naeem, P Inchausti, J Bengtsson, J P Grime, A Hector, D U Hooper, et al. 2001. “Biodiversity and Ecosystem Functioning: Current Knowledge and Future Challenges.” *Science (New York, N.Y.)* 294 (5543): 804–8. https://doi.org/10.1126/science.1064088.

Luvuno, LB, DC Kotze, and KP Kirkman. 2016. “Long-Term Landscape Changes in Vegetation Structure: Fire Management in the Wetlands of KwaMbonambi, South Africa.” *African Journal of Aquatic Science* 41 (3): 279–88. https://doi.org/10.2989/16085914.2016.1177482.

Maciejewski, Kristine, and Graham I H Kerley. 2014. “Understanding Tourists’ Preference for Mammal Species in Private Protected Areas: Is There a Case for Extralimital Species for Ecotourism?” *PLoS ONE* 9 (2). https://doi.org/10.1371/journal.pone.0088192.

Marks, Shula. 1967. “Review : The Nguni , The Natalians , and Their History Reviewed Work (s): A History of Natal by E . H . Brookes and C . de B . Webb ; The Washing of the Spears : The Rise and Fall of the Zulu Nation by Donald R . Morris ; The Zulu Aftermath : A Nineteen.” *The Journal of African History* 8 (3): 529–40.

Meadows, Donella. 2003. *Thinking in Systems: A Primer*. London: Chelsea Green Publishing. https://books.google.co.za/books/about/Thinking_in_Systems.html?id=JSgOSP1qklUC&pgis=1.

Meyer, Katrin M., Kerstin Wiegand, and David Ward. 2009. “Patch Dynamics Integrate Mechanisms for Savanna Tree–grass Coexistence.” *Basic and Applied Ecology* 10 (6): 491–99. https://doi.org/10.1016/j.baae.2008.12.003.

Millennium Ecosystem Assessment. 2005. “Ecosystems and Human Well-Being: Synthesis.” Washington, DC.

Mucina, L., and M. C. Rutherford. 2006. *The Vegetation of South Africa, Lesotho and Swaziland*. South African National Biodiversity Institute.

Nackley, Lloyd L, Amy Betzelberger, Andrew Skowno, Adam G West, Brad S Ripley, William J Bond, and Guy F Midgley. 2018. “CO 2 Enrichment Does Not Entirely Ameliorate Vachellia Karroo Drought Inhibition: A Missing Mechanism Explaining Savanna Bush Encroachment.” *Environmental and Experimental Botany* 155: 98–106. https://doi.org/10.1016/j.envexpbot.2018.06.018.

Nyström, Magnus, Albert V. Norström, Thorsten Blenckner, Maricela de la Torre-Castro, Johan S. Eklöf, Carl Folke, Henrik Österblom, Robert S. Steneck, Matilda Thyresson, and Max Troell. 2012. “Confronting Feedbacks of Degraded Marine Ecosystems.” *Ecosystems* 15: 695–710. https://doi.org/10.1007/s10021-012-9530-6.

O’Connor, Tim G, James R Puttick, and M Timm Hoffman. 2014. “Bush Encroachment in Southern Africa : Changes and Causes.” *African Journal of Range and Forage Science* 31 (October): 67–88. https://doi.org/10.2989/10220119.2014.939996.

Polley, H W. 1997. “Implications of Rising Atmospheric Carbon Dioxide Concentration for Rangelands.” *Journal of Range Management* 50 (6): 562–77. https://doi.org/10.2307/4003450.

Ratajczak, Zak, Jesse B Nippert, John M Briggs, and John M Blair. 2014. “Fire Dynamics Distinguish Grasslands , Shrublands and Woodlands as Alternative Attractors in the Central Great Plains of North America,” 1374–85. https://doi.org/10.1111/1365-2745.12311.

Raudsepp-Hearne, Ciara, Garry D. Peterson, Maria Tengö, Elena M. Bennett, Tim Holland, Karina Benessaiah, Graham K. MacDonald, and Laura Pfeifer. 2010. “Untangling the Environmentalist’s Paradox: Why Is Human Well-Being Increasing as Ecosystem Services Degrade?” *BioScience* 60 (8): 576–89. https://doi.org/10.1525/bio.2010.60.8.4.

Rockström, Johan, Will Steffen, Kevin Noone, Asa Persson, F Stuart Chapin, Eric F Lambin, Timothy M Lenton, et al. 2009. “A Safe Operating Space for Humanity.” *Nature* 461 (7263): 472–75. https://doi.org/10.1038/461472a.

Roques, K.G. G, T.G. G O’Connor, and A.R. R Watkinson. 2001. “Dynamics of Shrub Encroachment in an African Savanna: Relative Influences of Fire, Herbivory, Rainfall and Density Dependence.” *Journal of Applied Ecology* 38 (2): 268–80. https://doi.org/10.1046/j.1365-2664.2001.00567.x.

Russell, Jennifer M., and David Ward. 2014. “Remote Sensing Provides a Progressive Record of Vegetation Change in Northern KwaZulu-Natal, South Africa, from 1944 to 2005.” *International Journal of Remote Sensing* 35 (3): 904–26. https://doi.org/10.1080/01431161.2013.873154.

Ryan, Casey M, Rose Pritchard, Iain McNicol, Matthew Owen, Janet A Fisher, and Caroline Lehmann. 2016. “Ecosystem Services from Southern African Woodlands and Their Future under Global Change.” *Phil. Trans. R. Soc. B* 371: 20150312. https://doi.org/10.1098/rstb.2015.0312.

Sankaran, Mahesh, Niall P Hanan, Robert J Scholes, Jayashree Ratnam, David J Augustine, Brian S Cade, Jacques Gignoux, et al. 2005. “Determinants of Woody Cover in African Savannas.” *Nature* 438 (7069): 846–49. https://doi.org/10.1038/nature04070.

Sankaran, Mahesh, Jayashree Ratnam, and Niall P. Hanan. 2004. “Tree-Grass Coexistence in Savannas Revisited - Insights from an Examination of Assumptions and Mechanisms Invoked in Existing Models.” *Ecology Letters* 7 (6): 480–90. https://doi.org/10.1111/j.1461-0248.2004.00596.x.

Scheffer, M, S Carpenter, J A Foley, C Folke, and B Walker. 2001. “Catastrophic Shifts in Ecosystems.” *Nature* 413 (6856): 591–96. https://doi.org/10.1038/35098000.

Scheffer, Marten, Jordi Bascompte, William A Brock, Victor Brovkin, Stephen R Carpenter, Vasilis Dakos, Hermann Held, Egbert H van Nes, Max Rietkerk, and George Sugihara.

2009. “Early-Warning Signals for Critical Transitions.” *Nature* 461 (7260): 53–59. https://doi.org/10.1038/nature08227.

Scheffer, Marten, and Stephen R. Carpenter. 2003. “Catastrophic Regime Shifts in Ecosystems: Linking Theory to Observation.” *Trends in Ecology & Evolution* 18 (12): 648–56. https://doi.org/10.1016/j.tree.2003.09.002.

Scholes, R.J. 2003. “Convex Relationships in Ecosystems Containing Mixtures of Trees and Grass.” *Environmental and Resource Economics* 26 (4): 559–74. https://doi.org/10.1023/B:EARE.0000007349.67564.b3.

Shackleton, Ross, Charlie Shackleton, Sheona Shackleton, and James Gambiza. 2013. “Deagrarianisation and Forest Revegetation in a Biodiversity Hotspot on the Wild Coast, South Africa.” *PloS One* 8 (10): e76939. https://doi.org/10.1371/journal.pone.0076939.

Silveira Pontes, Laíse da, Danièle Magda, Marc Jarry, Benoît Gleizes, and Cyril Agreil. 2012. “Shrub Encroachment Control by Browsing: Targeting the Right Demographic Process.” *Acta Oecologica* 45 (November): 25–30. https://doi.org/10.1016/j.actao.2012.08.006.

Skowno, Andrew L., Mark W. Thompson, Jens Hiestermann, Brad Ripley, Adam G. West, and William J. Bond. 2017. “Woodland Expansion in South African Grassy Biomes Based on Satellite Observations (1990–2013): General Patterns and Potential Drivers.” *Global Change Biology* 23 (6): 2358–69. https://doi.org/10.1111/gcb.13529.

Staver, A. Carla, William J. Bond, William D. Stock, Sue J. van Rensburg, and Matthew S. Waldram. 2009. “Browsing and Fire Interact to Suppress Tree Density in an African Savanna.” *Ecological Applications* 19 (7): 1909–19. https://doi.org/10.1890/08-1907.1.

Staver, Ann Carla, and William J. Bond. 2014. “Is There a ‘Browse Trap’? Dynamics of Herbivore Impacts on Trees and Grasses in an African Savanna.” Edited by Amy Austin. *Journal of Ecology* 102 (3): 595–602. https://doi.org/10.1111/1365-2745.12230.

Steffen, W. L., R. A. Sanderson, P. D. Tyson, J. Jäger, P. A. Matson, B. Moore, F. Oldfield, et al. 2004. *Global Change and the Earth System : A Planet under Pressure*. Springer. http://www.igbp.net/publications/igbpbookseries/igbpbookseries/globalchangeandtheearthsystem2004.5.1b8ae20512db692f2a680007462.html.

Steffen, W., K. Richardson, J. Rockstrom, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, et al. 2015. “Planetary Boundaries: Guiding Human Development on a Changing Planet.” *Science* 347 (6223): 1259855. https://doi.org/10.1126/science.1259855.

Steffen, Will, Åsa Persson, Lisa Deutsch, Jan Zalasiewicz, Mark Williams, Katherine Richardson, Carole Crumley, et al. 2011. “The Anthropocene: From Global Change to Planetary Stewardship.” *Ambio* 40: 739–61. https://doi.org/10.1007/s13280-011-0185-x.

Stevens, Nicola, B. F. N. Erasmus, S. Archibald, and W. J. Bond. 2016. “Woody Encroachment over 70 Years in South African Savannahs: Overgrazing, Global Change or Extinction Aftershock?” *Philosophical Transactions of the Royal Society B: Biological Sciences* 371 (1703): 20150437. https://doi.org/10.1098/rstb.2015.0437.

Stevens, Nicola, Caroline E. R. Lehmann, Brett P. Murphy, and Giselda Durigan. 2017. “Savanna Woody Encroachment Is Widespread across Three Continents.” *Global Change Biology* 23 (1): 235–44. https://doi.org/10.1111/gcb.13409.

Tefera, Solomon, B.J. Dlamini, and A.M. Dlamini. 2008. “Dynamics of Savannas in Swaziland: Encroachment of Woody Plants in Relation to Land Use and Soil Classes and

Indigenous Knowledge on Plants Utilization." *Research Journal of Botany* 3 (2): 49–64. https://doi.org/10.3923/rjb.2008.49.64.

Troell, Max, Leif Pihl, Patrik Rönnbäck, Håkan Wennhage, Tore Söderqvist, and Nils Kautsky. 2005. "Regime Shifts and Ecosystem Services in Swedish Coastal Soft Bottom Habitats: When Resilience Is Undesirable." https://dlc.dlib.indiana.edu/dlc/bitstream/handle/10535/3083/30.pdf?sequence=1&isAllowed=y.

Uys, Roger G, William J Bond, and Theresa M Everson. 2004. "The Effect of Different Fire Regimes on Plant Diversity in Southern African Grasslands." *Biological Conservation* 118 (4): 489–99. https://doi.org/10.1016/j.biocon.2003.09.024.

Venter, Z. S., M. D. Cramer, and H.-J. Hawkins. 2018. "Drivers of Woody Plant Encroachment over Africa." *Nature Communications* 9 (1): 2272. https://doi.org/10.1038/s41467-018-04616-8.

Villiers, a.D. de, and T. O'Connor. 2010. "Fire-Mediated Succession and Reversion of Woody Vegetation in the KwaZulu-Natal Drakensberg, South Africa." *Grassroots* 10 (3): 18–21.

Walker, Brian, C. S. Holling, Stephen R. Carpenter, and Ann Kinzig. 2004. "Resilience, Adaptability and Transformability in Social – Ecological Systems." *Ecology and Society* 9 (2): 5. https://doi.org/10.1103/PhysRevLett.95.258101.

Ward, D. 2005. "Do We Understand the Causes of Bush Encroachment in African Savannas?" *African Journal of Range & Forage Science* 22 (2): 101–5. https://doi.org/10.2989/10220110509485867.

Ward, David, Kerstin Wiegand, and Stephan Getzin. 2013. "Walter's Two-Layer Hypothesis Revisited: Back to the Roots!" *Oecologia* 172 (3): 617–30. https://doi.org/10.1007/s00442-012-2538-y.

Wiegand, K, D Saltz, and D Ward. 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): 229–42. https://doi.org/10.1016/j.ppees.2005.10.001.

Wigley, B. J., W. J. Bond, and M. T. Hoffman. 2009. "Bush Encroachment under Three Contrasting Land-Use Practices in a Mesic South African Savanna." *African Journal of Ecology* 47: 62–70. https://doi.org/10.1111/j.1365-2028.2008.01051.x.

Wigley, Benjamin J., William J. Bond, and M. Timm Hoffman. 2010. "Thicket Expansion in a South African Savanna under Divergent Land Use: Local vs. Global Drivers?" *Global Change Biology* 16 (3): 964–76. https://doi.org/10.1111/j.1365-2486.2009.02030.x.

Wyk, BE van. 2002. "A Review of Ethnobotanical Research in Southern Africa" 68 (1): 1–13.

CHAPTER 2: WOODY ENCROACHMENT AS A SOCIAL-ECOLOGICAL REGIME SHIFT

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2.1 ABSTRACT

African savannas are increasingly affected by woody encroachment, an increase in the density of woody plants. Woody encroachment often occurs unexpectedly, is difficult to reverse, and has significant economic, cultural and ecological implications. The process of woody encroachment represents a so-called regime shift that results from feedback loops that link vegetation and variables such as fire, grazing and water availability. Much of the work on woody encroachment has focused on the direct drivers of the process, such as the role of fire or grazing in inhibiting or promoting encroachment. However, little work has been done on how ecological changes may feedback to affect some of the underlying social processes driving woody encroachment. In this paper we build on the ecological literature on encroachment to present a qualitative systems analysis of woody encroachment as a social-ecological regime shift. Our analysis highlights the underlying indirect role of human population growth, and we distinguish the key social-ecological processes underlying woody encroachment in arid versus mesic African savannas. The analysis we present helps synthesize the impacts of encroachment, the drivers and feedbacks that play a key role and identify potential social and ecological leverage points to prevent or reverse the woody encroachment process.

Keywords: *Savanna; Africa; alternate state; woody encroachment; ecosystem services; leverage points*

2.2 INTRODUCTION

Woody encroachment has been a problem in both southern African savannas (O'Connor, Puttick and Hoffman, 2014) and globally for over a century (Anadón *et al.*, 2014), and appears to be increasing in many regions (Bond and Midgley, 2012; Twidwell *et al.*, 2013). Savannas are mixed tree-grass systems that are characterised by a continuous grass layer and a discontinuous tree layer (Ratnam *et al.*, 2011), and support a range of livelihoods, economic activities and biodiversity (Anadón *et al.*, 2014; Honda *et al.*, 2016). Savannas are home to 505 million people in Africa, most of whom rely directly on these ecosystems for their livelihoods (Chidumayo and Gumbo, 2010). Woody encroachment is a shift from a grassy savanna to a persistently woody savanna, and typically involves indigenous woody species rather than invasive alien species (Bond and Midgley, 2012; O'Connor, Puttick and Hoffman, 2014). Woody encroachment threatens the provision of ecosystem services such as food and clean water, grazing for livestock farming, and habitats for some of the world's last remaining mega herbivores (Wigley, Bond and Hoffman, 2009; Gray and Bond, 2013; Honda *et al.*, 2016).

There is growing consensus that managing anthropogenic impacts on ecosystems and the services they provide requires a better understanding of the interactions between ecological and social systems (Reyers *et al.*, 2013). Much of the research on woody encroachment has focused on ecological drivers, especially the impact of disturbance (e.g. fire and grazing) and water availability on tree establishment and persistence (Higgins *et al.*, 2007; Sankaran, Ratnam and Hanan, 2008; Buitenwerf, Bond, Stevens and Trollope, 2012; Archibald, 2013). Few papers explicitly consider the role of social processes underlying these ecological changes, how ecological changes can feedback to affect the underlying social processes. In this paper we build on the ecological understanding of woody encroachment, to develop a broader social-ecological understanding of the dynamics underlying woody encroachment.

One way to conceptualise, the process of woody encroachment is to view it as a regime shift (Scheffer *et al.*, 2001; Folke *et al.*, 2004; Walker *et al.*, 2004; Levin *et al.*, 2012). Regime shifts are large, persistent changes in the structure and function of ecological or social-ecological systems (SES) (Scheffer *et al.*, 2001; Folke *et al.*, 2004)**.** SES dynamics result from feedback loops involving both ecological processes (the interaction between abiotic and biotic factors driving the system) and social processes (human behaviour and institutional processes influencing the system) (Levin, 1998; Walker *et al.*, 2004; Lade *et al.*, 2015). SES have several competing feedback loops operating simultaneously, including both balancing and reinforcing feedbacks. Reinforcing feedback loops are amplifying, self-multiplying processes that can be positive or negative and hence cause growth or runaway collapse over time (Meadows, 2003; Hull, Tuanmu and Liu, 2015). Balancing feedback loops decrease or reverse change in a system, and can be sources of stability as well as resistance to change. The set of feedback loops that dominate the system at a particular time will determine the system's present regime (Figure 2.1) (Meadows, 2003). A particular regime is characterised by a specific systemic structure and set of functions, and is created and maintained by a particular set of feedback loops.

A regime shift can occur when there is a change in the set of dominant feedback loops. This can occur for two reasons. Firstly, due to an external shock such a drought, and secondly, due to a gradual change in drivers that slowly weaken the dominant system feedbacks that maintain a particular regime (Folke *et al.*, 2004; Crépin *et al.*, 2012). Slow changes may gradually weaken the dominant feedbacks with no visible system change until an external shock hits the system, causing it to cross a critical threshold and move into an alternate regime (Figure 2.1). The drivers that affect system feedbacks can be internal, within a feedback loop and influenced by the feedback; or external, outside the feedback loops and not influenced by changes in the SES (Meadows, 2003). Most often a regime shift results from a combination of a shock and gradual changes in internal and external drivers. Regime shifts often have substantive impacts on the suite of ecosystem services provided by an ecosystem or SES, and consequently on human well-being (Millennium Ecosystem Assessment, 2005; Biggs *et al.*, 2012).

Reversing a regime shift requires sufficient understanding of the system to know which feedbacks are, and were, dominant and what actions or drivers can break unwanted feedback loops or recreate lost feedback loops. The strength of the dominant feedbacks determines how easy it is to reverse a specific regime shift (Biggs, Schlüter and Schoon, 2015). It is also important to note that the threshold levels of drivers that trigger a shift from one regime to another may differ from the threshold needed to shift the system back. This is known as hysteresis and characterizes many regime shifts (Scheffer *et al.*, 2001; Biggs *et al.*, 2012).

The objective of this paper is to review woody encroachment in African savannas using a social-ecological regime shift lens. We identify the key drivers, feedbacks and thresholds using the Biggs regime shifts analysis framework (Biggs, Peterson and Rocha, 2018). We specifically examine the ecological and social processes underlying encroachment and how changes in these processes weaken or strengthen social and ecological feedbacks in arid versus mesic savannas. This analysis allows us to identify leverage points – or places to intervene - for preventing or reversing woody encroachment in different contexts.

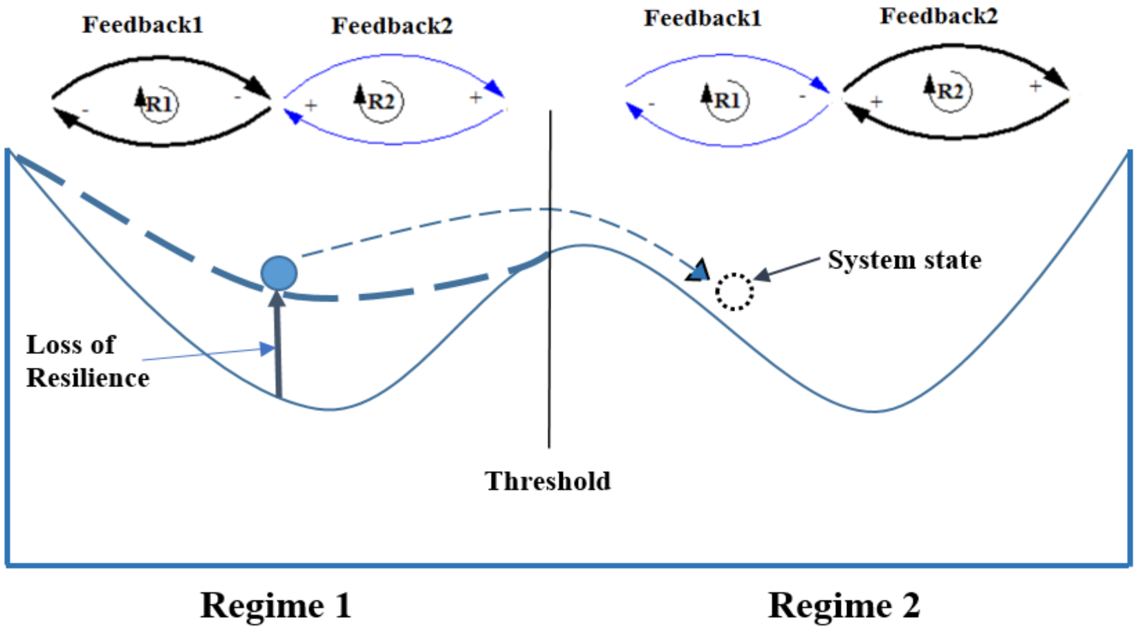

Figure 2.1: A simplified illustration of a regime shift. *R1 represents the dominant feedback loop in the system in regime 1. Over time, as the system variables and drivers change, the strength of feedback 1 may be reduced, leading to a loss of resilience. At some point, the system may cross a critical threshold and shift into regime 2 where feedback 2 is dominant. The cup represents a particular regime and the ball represents the ecosystem state at a certain point in time. The loss of resilience is represented by a change in the shape of the cup.*

2.3 Methods

To identify relevant literature on woody encroachment we performed a bibliographic search using Scopus (http://www.info.sciverse.com/). We searched for the key terms "woody encroachment and savanna" and "bush encroachment and savanna". The eligibility criteria included all types of documents: peer reviewed papers, books and book chapters, published between 01 /01/1984 and 31/12/2015 with the defined terms in the title, keywords or abstract. The papers were imported into the online systematic review software product Covidence (https://www.covidence.org/) for screening. We removed duplicates and papers which mentioned the search terms but were not relevant to our search, e.g papers on alien invasive species and the invasion of trees into grasslands (as opposed to savannas). We then filtered the papers to those dealing specifically with African savannas. The selected papers were read in full, and variables and their interactions were captured in a qualitative systems model. For each paper we recorded the proposed driver of woody encroachment and classified these into fire, grazing, browsing, moisture, tree-thinning/harvesting, temperature, tree density, CO2, and nutrients.

We used the Regime Shift Database framework (RSDB, www.regimeshifts.org) to synthesize existing literature on woody encroachment in savannas from an SES perspective (Figure 2.2). We chose the RSDB framework because it draws strongly on a systems-based understanding of the dynamics underlying regime shifts. The RSDB framework systematically analyses regime shifts based on their drivers, underlying feedbacks, impacts and management options. A key aspect of the RSDB approach is the development of a causal loop diagram (CLD) which synthesizes the key drivers and internal feedbacks in a system based on the literature (Meadows, 2003). The CLD is accompanied by a description which includes the definition of the system and a description of the alternate regimes, the feedbacks that maintain each regime, and the drivers of the regime shift in the system. Also included are leverage points and management options for preventing, reversing or facilitating a shift. To develop the CLD, we complemented the literature from the bibliographic search with understanding from additional relevant literature on the dynamics of savanna ecosystems.

To demonstrate the distribution of arid/semi-arid savannas and mesic savannas we plotted mean annual rainfall across Africa. We used the divide of ~700 mm as a boundary to delineate the distribution of these two savanna types (Sankaran *et al.*, 2005; Staver, Archibald and S. a. Levin, 2011), with savannas receiving less than 700 mm being defined as semi-arid and arid savannas and areas receiving more than 700 mm as mesic savannas. We overlaid the distribution of savannas onto this map, using the savanna distribution defined by (Lehmann *et al.*, 2011).

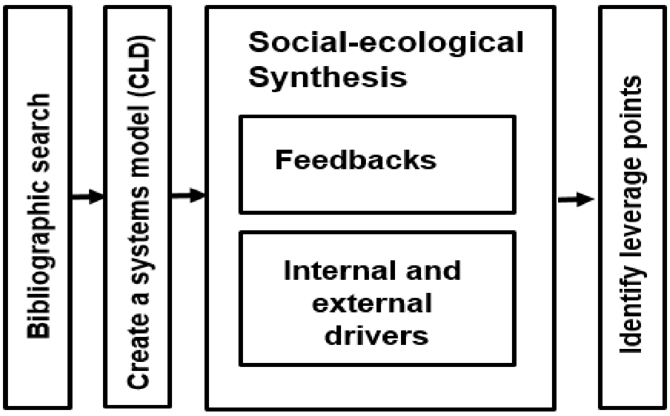

Figure 2.2: Summary of the steps used to synthesize the literature using a social-ecological systems lens.

2.4 REGIME SHIFT SYNTHESIS

The search "bush encroachment and savanna" and "woody encroachment and savanna" returned a total of 318 papers. Of the 318 papers, 232 reported on work in African systems. 74% investigated the drivers of woody encroachment, with fire and grazing as the most commonly (45 and 40 papers respectively) cited drivers (Figure 2.3).

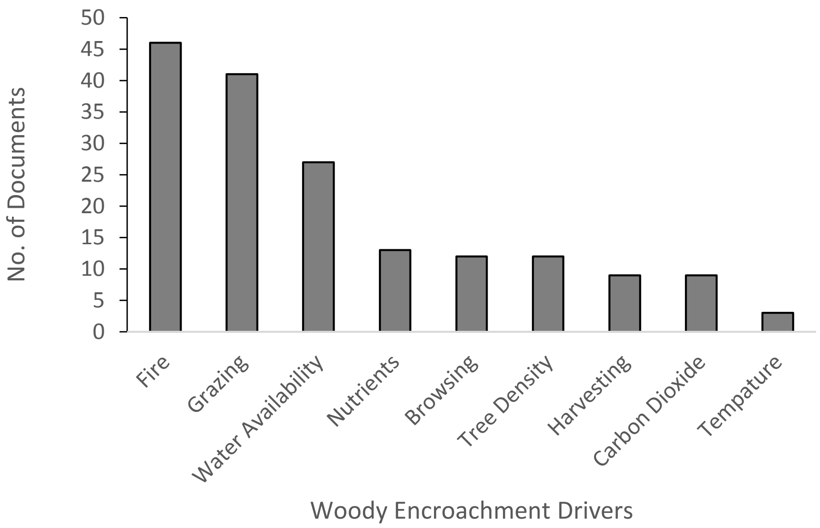

Figure 2.3: Number of documents reporting significant impacts of different drivers of woody encroachment.

Based on these documents we developed a conceptual model of the main ecological and social processes underlying woody encroachment in African savanna systems (Figure 2.4). We used this as the basis for developing a CLD (Figure 2.5), and identifying feedbacks, drivers, and leverage points of woody encroachment. Below we first describe the two alternate regimes based on the dominant feedback loops and drivers we identified, and then discuss the key feedbacks that sustain each regime, the internal and external drivers that can lead to a regime shift, and finally conclude with a discussion of the potential leverage points.

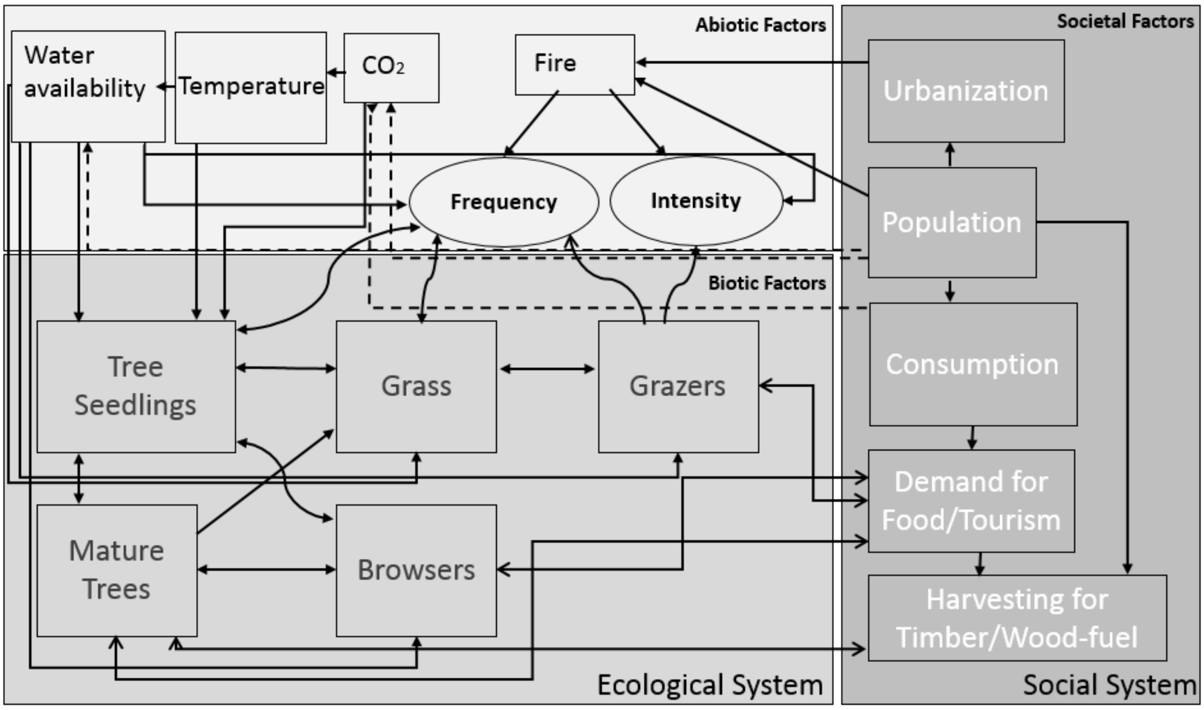

Figure 2.4: A simplified conceptual model illustrating the main processes and feedbacks that underlie woody encroachment regime shifts in a savanna social-ecological system.

2.4.1 Alternative regimes: Grassy and woody

It is well documented that savannas can exist in two alternate self-reinforcing regimes (Scheffer *et al.*, 2001; Scholes, 2003): a grass dominated regime and a tree/shrub dominated regime. The grassy savanna regime consists of an herbaceous layer dominated by C4 grass species and a discontinuous tree layer (Ratnam *et al.*, 2011). The grassy regime is maintained by frequent fire that topkills tree saplings and prevents them from reaching heights where they are no longer affected by fire. Grassy savannas are typically used as grazing lands for livestock and free-ranging wildlife.

The woody regime is dominated by woody shrubs or trees (Ratnam *et al.*, 2011). Once established, woody vegetation persists because adult trees are seldom killed by herbivory or fire (Higgins *et al.*, 2000). The woody regime may cover large continuous areas or be expressed as a mosaic of small patches of woody plants interspersed within open savannas. These respective patches are often highly persistent over time (Rietkerk *et al.*, 2004). Woody savannas are primarily used for wood and non-wood forest products that provide fuel, food, medicines and raw materials for building, crafts, and tools.

2.4.2 Feedback Mechanisms

Each of the regimes are dominated by particular feedbacks that determine the vegetation structure (Figure 2.5). The dominant processes differ between arid and mesic savannas (Figure 2.6). Arid savannas receive less than ~700 mm of rain and maximum tree cover is constrained by water availability (Sankaran *et al.*, 2005). Mesic savannas receive over 700 mm of rain, so there is sufficient water availability for canopy closure but this is prevented by the action of fire and herbivory (Sankaran *et al.*, 2005).

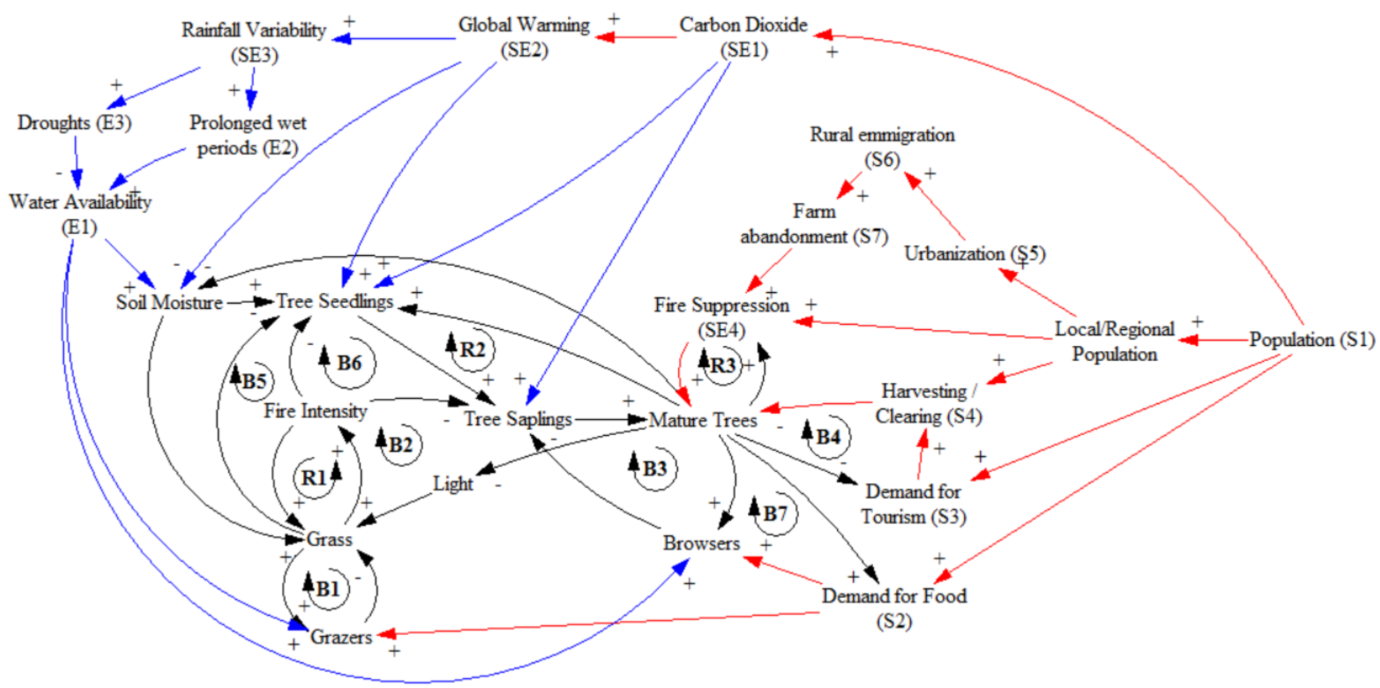

Figure 2.5: Causal loop diagram illustrating key feedbacks and drivers underlying woody encroachment in savanna systems. *Red links denote external anthropogenic drivers, blue links denote social-ecological drivers, and black links are internal system interactions and feedbacks. R denotes a reinforcing feedback loop and B a balancing feedback loop. The arrow heads have polarity signs indicating whether the relationship is one that leads to either increases (+) or decreases (-) in the state variables. S refers to largely social drivers, SE to social ecological drivers and E refers to ecological drivers.*

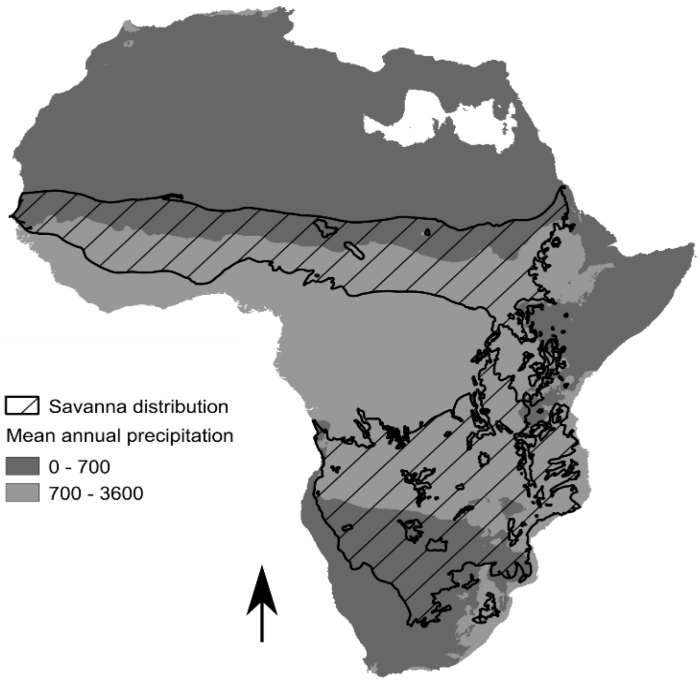

Figure 2.6: The distribution of arid/semi-arid and mesic savannas across Africa.

2.4.3 Grassy regime

This regime is dominated by the fire feedback (R1) (Sankaran *et al.*, 2005). Fire rarely kills mature trees but has a negative impact on the seedling and sapling regeneration of woody plants (Higgins *et al.*, 2000, 2007; Bond and Keeley, 2005; Van Auken, 2009). Frequent fire prevents saplings from escaping the fire trap where they remain reproductively immature (Higgins *et al.*, 2000). Tree saplings can spend decades in this immature state where they are not able to resprout quickly enough to escape frequent fires. Fire therefore reduces the number of seedlings and tree density in the system, and prevents canopy closure which ensures there is sufficient light for C4 grasses. Fire is particularly important in mesic savannas as a reinforcing feedback as there is sufficient rainfall for canopy closure to occur (Sankaran *et al.*, 2005; Staver, Archibald and S. Levin, 2011). Arid savannas have a lower fire frequency due to lower grass productivity (Archibald *et al.*, 2009), as water and nutrients are a limiting factor which prevents canopy closure (Sankaran *et al.*, 2005). Although fire is an ecological element, the extent, frequency and intensity of fire is largely determined by anthropogenic factors. Human population size and land use have a substantial impact on the fire regime by influencing fire frequency, season, and location which influences fire intensity (Archibald, Staver and Levin, 2012). A high grass biomass (which is affected by the soil moisture and nutrients, light and grazers feedbacks), causes more frequent and intense fires (Sankaran *et al.*, 2005; Archibald *et al.*, 2009). The number of grazers (especially cattle) are in turn affected by demand for food, consumption preferences, access to land and different institutional arrangements based on land use and value systems (Fernandez *et al.*, 2002; Bennett, 2013; Hedenus, Wirsenius and Johansson, 2014).

2.4.3 Woody regime

This regime is dominated by two reinforcing feedbacks, the micro-climates/recruitment feedback (R2) which dominates in arid savannas and the fire suppression feedback (R3) which is most likely to occur in mesic savannas. The fire suppression feedback is directly affected by fire policies, which are related to regional population growth and urbanization.

In arid savannas, tree recruitment occurs when seed availability and high rainfall events occur over the same spatial area (Kraaij and Ward, 2006; Joubert, Rothauge and Smit, 2008), and facilitation can outweigh competition for resources (Rietkerk *et al.*, 2004; Dohn *et al.*, 2013). Facilitation occurs when existing mature trees trap and retain nutrients and water by lowering evaporation and increasing infiltration through shading and root penetration, creating a microclimate that fosters tree recruitment (Rietkerk *et al.*, 2004; Dohn *et al.*, 2013). Additionally, established trees have a positive effect on each other by accumulating local water deeper in the soil profile and nutrients from the surroundings and creating “islands of fertility” (Rietkerk *et al.*, 2004; Wiegand, Saltz and Ward, 2006). However, inter tree competition for resources can also reduce tree growth in arid savannas (Dohn *et al.*, 2013).

In mesic savannas where canopy closure is possible, fire suppression (through fire legislation and land management strategies) allows saplings to escape the demographic bottleneck and establish as mature trees where they can no longer be killed by fire or herbivory (Higgins *et al.*, 2000). Once woody cover surpasses ~40%, light attenuation occurs (Meyer *et al.*, 2007; Dohn *et al.*, 2013). A reduction of light reduces C4 grass biomass as they are adapted to greater light intensity (Sage, 2004). This creates a powerful reinforcing loop as a decline in grass biomass leads to reduced fire intensity and frequency (Archibald *et al.*, 2009), which further favours woody plant establishment.

2.5 DRIVERS OF WOODY ENCROACHMENT

Woody encroachment has been attributed to a variety of processes which can be encompassed in two models: demographic bottleneck models and competition-based models. Demographic-bottleneck models emphasise the impact of disturbance and water availability on tree establishment and persistence (Higgins *et al.*, 2000; Sankaran, Ratnam and Hanan, 2004; Wiegand, Saltz and Ward, 2006; O'Connor, Puttick and Hoffman, 2014). Competition-based models, as the name suggests, emphasise competitive interaction in determining tree-grass co-existence, with co-existence resulting from spatial or temporal niche separation (Scholes and Archer, 1997; Sankaran, Ratnam and Hanan, 2004; Ward, Wiegand and Getzin, 2013; O'Connor, Puttick and Hoffman, 2014).

The drivers of woody encroachment can be categorized into internal system changes, external drivers and shocks. A recent review of 23 studies by (O'Connor, Puttick and Hoffman, 2014) concludes that the occurrence of woody encroachment depends on the interplay of these shocks, internal and external drivers; recognition of this is essential for containing encroachment. These drivers play different roles in enabling, initiating and sustaining woody encroachment depending on the processes they influence in the broader social-ecological system.

2.5.1 Internal system changes

There are a set of well-established internal system drivers that can push a savanna towards either a grassy or woody regime. These include changes in tree density, grazers, browsers and soil moisture. All of these affect fire frequency and intensity.

2.5.1.1 Tree Density

Tree density changes slowly but affects and responds to the micro-climate/recruitment feedback (R2) and the fire suppression feedback (R3) that are dominant in the woody regime. Changing tree density also influences fire behaviour (Van Langevelde *et al.*, 2003), which is affected by grass biomass, rainfall variability and seasonality, tree cover, topography, grazing (Van Langevelde *et al.*, 2003; Archibald *et al.*, 2009; D'Antonio *et al.*, 2009).

2.5.1.2 Grazers and browsers

Grazing and browsing are a natural component of savanna systems, but the number of grazers (especially cattle) and browsers are affected by demand for food, consumption preferences, access to land and different institutional arrangements based on land use and value systems (Fernandez *et al.*, 2002; Bennett, 2013; Hedenus, Wirsenius and Johansson, 2014). Sustained heavy grazing by livestock ranching promotes woody seedling regeneration through reduced grass competition, provided that seedling mortality is not increased through consumption and trampling, and there has been above average rainfall in more arid savannas (Skarpe, 1990; Higgins *et al.*, 2007; O'Connor, Puttick and Hoffman, 2014). Heavy grazing in mesic savannas reduces fuel load through consumption and trampling, thereby reducing fire frequency and more significantly fire intensity (Higgins *et al.*, 2000; Roques, O'Connor and Watkinson, 2001; Wiegand, Saltz and Ward, 2006; Archibald *et al.*, 2009; O'Connor, Puttick and Hoffman, 2014). Overgrazing has also been reported to reduce the effect of grass competition on tree seedlings and saplings, as a dense grass layer can negatively affect tree growth and survival (Ward and Esler, 2011; February and Higgins, 2013; Tedder *et al.*, 2014). Long term grazing trials in both mesic and arid systems have consistently reported increases in the density of woody plants over 5 – 40 year periods of observation (Skarpe, 1990).

The loss of browsers due to anthropogenic landscape changes and hunting, especially the loss of mega-herbivores such as elephants, is thought to be one of the major drivers of woody encroachment (Bond, 2008; O'Connor, Puttick and Hoffman, 2014). Bark-stripping and uprooting of trees by elephants can result in mortality of adult trees and seedlings, and maintain plants within flame height (O'Connor *et al.*, 2007; O'Connor, Puttick and Hoffman, 2014). Browsing of seedlings, on its own, appears capable of containing woody encroachment under some circumstances (Sankaran, Ratnam and Hanan, 2008; Staver *et al.*, 2009; O'Connor, Puttick and Hoffman, 2014), by minimizing the dominance of the micro-climates/recruitment feedback (Staver and Bond, 2014). Recent research has empirically shown the impact of the loss of mega-herbivores (Daskin, Stalmans and Pringle, 2016; Stevens *et al.*, 2016; Skowno *et al.*, 2017). The release of trees from browsing pressure in a study in Mozambique resulted in tree cover increases ranging from 57% to 134% over a 35 year time period –with no directional trend changes in fire and rainfall (Daskin, Stalmans and Pringle, 2016).

2.5.1.3 Soil Moisture

Water availability influences all of the components of the system and is the critical limiting factor to plant growth in savannas (Sankaran *et al.*, 2005). Any measure of plant productivity from phenology to growth rate relies on the amount of precipitation in the region (Jolly, Nemani and Running, 2005; Sankaran *et al.*, 2005). In arid savannas, increased soil moisture (high rainfall frequency) promotes seedling regeneration and establishment, and tends to favour the establishment of woody species (Ward, 2005; Kraaij and Ward, 2006; Wiegand, Saltz and Ward, 2006; Dohn *et al.*, 2013; O'Connor, Puttick and Hoffman, 2014). Joubert, Rothauge and Smit (2008), documents that three consecutive years of above average rainfall are necessary for the recruitment of woody species. This has also been reported in Australian semi-arid savannas and in bin experiments (Kraaij and Ward, 2006). In mesic savannas increased soil moisture contributes to increased grass biomass, therefore higher levels of grass competition, fuel loads and higher fire intensities (Sankaran *et al.*, 2005; Sankaran, Ratnam and Hanan, 2008; Van Auken, 2009; Vadigi and Ward, 2014), which maintain the grassy regime.

2.5.2 External drivers

External drivers include either social or socially driven ecological drivers (e.g. fire suppression or land use). These include quantifiable physical drivers such as population growth and tree harvesting, as well as complex emergent features which are difficult to quantify such as governance and worldviews or mental models. The latter tend to impact both the social drivers and the socially driven ecological drivers through legislation and value systems that have an impact on land use and institutional arrangements/management systems.

2.5.2.1 *Population growth and urbanization*

Human population growth can affect internal system variables and processes in ways that can either increase or decrease woody cover and the potential for encroachment. As human population grows, food demand increases incentives to increase cattle numbers, given current consumption preferences (Hedenus, Wirsenius and Johansson, 2014). Furthermore, in most African cultures, large cattle numbers represent power and wealth because they provide milk and meat, their droppings can be used as fuel for fires, and for plastering walls and floors in houses, and they are used as a form of money to pay fines and lobola (Shackleton *et al.*, 2005). At high densities, cattle reduce the grassy layer and fire frequency which facilitates tree establishment and hence encroachment (Higgins *et al.*, 2000, 2000; Archibald *et al.*, 2009).

A demand for wildlife tourism has led reserve managers to increase the number of certain game species that appeal to tourists (Castley, Boshoff and Kerley, 2001; Maciejewski and Kerley, 2014). The reestablishment of elephants in many reserves in South Africa has led to reductions in woody plant cover (O'Connor *et al.*, 2007; Guldemond, Van Aarde and Aarde, 2008).

Demand for tourism also influences tree cover as visibility of animals is a contributing factor for returning to a game reserve (Gray and Bond, 2013). Reserve managers therefore invest in tree clearing or increasing fire frequency to manage tree cover.

On the other hand, in many rural areas; food demand may also lead to an increase in browsers such as goats. Goats are the only livestock herbivore known to effectively reduce woody cover, and hence counteract encroachment (O'Connor, Puttick and Hoffman, 2014). Increased human populations also increase tree harvesting which reduces the amount of adult tree biomass in savanna system (Banks *et al.*, 1996; Madubansi and Shackleton, 2007). This has a direct impact on the microclimate/ recruitment feedback that reinforces woody growth.

As countries develop, they tend to restructure their economies away from agriculture into manufacturing and services (Christiaensen and Todo, 2014). With the world rapidly urbanizing, 50% of the population in developing countries is estimated to be living in cities by 2020 (Christiaensen, De Weerdt and Todo, 2013). Deagrarianisation in large parts of South African communal areas has resulted in a significant increase in woody encroachment in abandoned cultivated fields (Shackleton *et al.*, 2013; Hoffman, 2014), and this is likely to happen elsewhere as well as rural areas depopulate.

2.5.2.2 Land-use, institutional arrangements and worldviews

Management practices and institutional arrangements are based on specific mental models or worldviews that draw on scientific understanding and local ecological knowledge. Mental models reflect our understanding of how a system works: the interactions between factors or components, the critical issues, and the causal links (Lynam and Brown, 2012).

In early colonial days, fire suppression laws were passed in southern Africa which were based on European attitudes/worldview towards fire. These views were amplified by the Drought Investigation Commision report in 1926 which promoted the view that fire was undesirable in savannas (van Wilgen *et al.*, 2010; O'Connor, Puttick and Hoffman, 2014). Fire suppression refers to the reduction in the frequency and intensity of fire in a system compared with the natural or historic fire regime. As fire has a strong negative impact on tree growth and recruitment, fire suppression promotes an increase in woody vegetation, reduces the dominance of the fire feedback and increases the dominance of the microclimates/recruitment feedback.

As the recognition of the importance of fire in African savannas became more apparent, a number of fire trials were set up across Africa in the 20th century. An analysis of 28 fire trial experiments, found that fire exclusion has an unequivocal influence on the increase of trees in savannas within a rainfall range of 386 – 1900 mm per annum (O'Connor, Puttick and Hoffman, 2014). Tree density increased by 5.8% more under fire exclusion compared with other burning regimes.

South Africa's changing social and political regimes and structures provide a great example of how interlinked social and ecological systems are. The Apartheid government forced the majority of black people into smaller portions of land which led to degradation in communally managed areas compared to privately owned white farmlands (Hoffman, 2014). A democratic government brought with it the freedom to live in any area which contributed to a rise in rural-urban migration as people move to cities in pursuit of better opportunities, and land reform structures which contributed to a significant portion of cultivated land being transferred to inexperienced and poorly supported farmers (Shackleton *et al.*, 2013; Hoffman, 2014). These changes have indirectly contributed to an increase in woody encroachment (Hoffman, 2014).

2.5.2.3 Carbon dioxide

Currently, the anthropogenically-driven warming climate and increased atmospheric carbon dioxide are thought to be the leading drivers of woody encroachment as they accelerate root growth and enhance sapling resprouting after fire. In addition, these drivers enhance tree water use efficiency, and can potentially extend the summer growing period which increases the survival rate of woody plants (Polley, 1997; Stevens *et al.*, 2014; Buitenwerf, Rose and Higgins, 2015). The underlying mechanism is still debated, but several possibilities have been proposed. The first hypothesis is that higher carbon dioxide (CO2) concentration levels favour C3 (woody plant) photosynthesis relative to C4 (tropical grass) photosynthesis which accelerates woody plant growth and can promote a faster escape of saplings from the fire trap (Polley, 1997; Buitenwerf, Rose and Higgins, 2015). This has been supported by evidence from multiple Free-Air Carbon Dioxide Enrichment (FACE) experiments which expose vegetation to elevated CO2 (Leakey *et al.*, 2009). A comparison of different ecosystem responses to elevated CO2 showed significant differences among arid savannas, grasslands and forests. On average, increases in above ground production were significantly greater in arid savannas than in forests and grasslands, with forests having greater net primary production than grasslands

(Nowak, Ellsworth and Smith, 2004). The second hypothesis is that higher CO2 levels may reduce transpiration of plants through reduced stomatal conductance, causing greater water filtration and increased soil water (Polley, 1997; Bond and Midgley, 2000); this is especially important in arid savannas as woody plants can produce more biomass for the same amount of rainfall (Polley, 1997; Leakey *et al.*, 2009; Stevens *et al.*, 2014).

2.5.3 Shocks

Drought plays an important role in woody encroachment by decreasing the likelihood of fires. As the grass dies and is grazed out there is seldom any fire (O'Connor, Puttick and Hoffman, 2014). An extreme drought reduces grass biomass and when rain does arrive, grass recovery is slow. During this time tree establishment can occur rapidly in the absence of grass competition (Kraaij and Ward, 2006; O'Connor, Puttick and Hoffman, 2014). In contrast, high rainfall frequencies in arid savannas give woody seedlings a competitive edge over grass. Seedling recruitment (R2) in arid savannas usually occurs during consecutive higher rainfall years (Kraaij and Ward, 2006). The frequency and intensity of drought and high rainfall events are being influenced by rising CO2 and a warming climate.

2.6 Management options and leverage points

Effective management needs to find points in the system to intervene, where a change in the system will produce the most gain. These are called leverage points. This requires a good knowledge of the system, including knowledge of variables, flows, delays in flows or response of variables, and different feedback loops (Meadows, 2003). Effective management centres on manipulating the flows and feedbacks in the system, taking account of possible delays. The key leverage points in savanna systems include manipulation of fire, browsing and manual clearing.

Manipulating the fire frequency strongly affects the tree/grass ratio, especially in mesic savannas. Increasing fire frequency in a system promotes grass regeneration which has a negative impact on tree seedling establishment through competition, and suppresses tree saplings to control tree dominance. Long term research suggests that normal fire regimes will not be able to curb the effects of CO2 (Buitenwerf, Bond, Stevens and Trollope, 2012), suggesting that higher fire intensities are required to prevent the spread of woody plants. Crowlely, Garnett and Shepard (2009) demonstrates that a fire regime that includes regular storm-burning (high intensity burning) can be effective for maintaining grassy savannas by preventing encroachment by trees (Crowlely, Garnett and Shepard, 2009). Smit *et al*. (2016) found repeated high-intensity late season fires greatly reduce tree cover over low to moderate intensity fires (Smit *et al.*, 2016). However, these high-intensity fires came at the expense of losing tall (5-10 m) trees which is not desired. Strategic use of high-intensity fires is therefore necessary to maintain a heterogeneous landscape.

Browsers (ranging from goats to elephants) can suppress woody growth, limit the establishment of woody seedlings, and reduce canopy cover (Dublin, 1986; Daskin, Stalmans and Pringle, 2016; Stevens *et al.*, 2016). The widespread elimination of megafauna e.g. elephants, and the overall reduction in the numbers of browsers, is considered a wide scale driver of tree cover increases in Africa (Staver and Bond, 2014; Daskin, Stalmans and Pringle, 2016). Reintroducing browsers back into savanna systems can have a negative impact on both mature trees and tree seedlings, and shift feedbacks in favour of the grassy regime.

Grass production declines more rapidly for initial increments in tree basal area than it does for subsequent increments (Scholes and Archer, 1997). With this knowledge, Scholes (2003) proposes that 40-50% tree cover in savanna systems is the threshold at which the system shifts from the grassy to the woody regime. This is due to the influence of fire on the spread, frequency and intensity of fire above a threshold of 45 to 50% tree cover (Staver, Archibald and Levin, 2011). Clearing trees and maintaining tree cover below 40% may be critical for preventing a shift from a grassy to a woody system. Tree clearing is an expensive endeavour and unrealistic in some systems (Smit *et al.*, 2016), but if done strategically in patches to increase grass cover and keep trees below 50% cover (Smit, 2004), over time this could weaken the micro-climate/recruitment (R2) and fire suppression (R3) feedback loops that help sustain the woody regime. Though clearing efforts are widely attempted, the costs of clearing are not generally reported in the literature (Angassa and Oba, 2009). Namibia estimates that the total cost for the control of woody encroachment through clearing is US$2.1 billion. A study on different clearing strategies of 29 woody species in Ethiopia concluded that the most effective rehabilitation strategy was clearing and fire combined with grazing (Angassa and Oba, 2009).

All the above leverage points involve manipulating internal system variables. Recent research documenting fence studies indicate that global change (particularly increased CO2) may be overriding local management (Wigley, Bond and Hoffman, 2010; Buitenwerf, Bond, Stevens and Trollope, 2012; Moncrieff *et al.*, 2014). Land use can be manipulated to yield different tree cover percentages. Currently, without excessive human intervention through mechanical clearing, fire storms or introducing elephants into the system; global drivers such as increased carbon dioxide concentration, which are driven by anthropogenic changes, are probably overriding the system.

2.7 Discussion and Conclusions

This review expands current ecological understanding of woody encroachment in savannas, to a broader social-ecological perspective. Considering woody encroachment as a social-ecological regime shift takes the focus away from single drivers and considers the broader system with an emphasis on the interconnections amongst underlying feedback processes, particularly the interplay between social and ecological processes.

Our analysis highlights that humans have both local and global influence on savannas, and that the increasing shift from grassy to woody savannas may ultimately be largely linked to growing human populations. Given current consumption preferences and technologies, growing human populations are linked to increased demand for livestock production as a source of food, and to increasing carbon dioxide emissions through various human activities. There is also a direct link between growing human populations and fire suppression. All of these factors mostly affect savanna systems in ways that increase the likelihood of woody encroachment.

Identifying key leverage points in the form of feedbacks and drivers is imperative for effectively managing savanna systems. Our analysis highlights that in mesic savannas, fire and fire-competition feedbacks maintain the grassy regime, while water is the limiting factor that prevents tree establishment in the arid savannas. A frequent fire regime which includes fire storms and strategic clearing are therefore key leverage points in maintaining a grassy regime. At a broader scale, influencing consumption preferences or technologies in ways that reduce grazing pressure and carbon dioxide emissions, could also play a key role in maintaining open savanna systems. The possibility of identifying both direct local and indirect global leverage points in an integrated way in a single analysis is a key strength of the RSDB framework.

The review focuses on woody encroachment in savannas, but similar processes can lead to shifts between biomes. In certain areas, grasslands, savannas and forests occur as alternate regimes under the same climatic conditions (Staver, Archibald and S. a. Levin, 2011), and shifts between them may occur when factors such as rainfall and fire frequency are altered (Bond, Woodward and Midgley, 2005; Bond, 2008). We suggest that the loss of C4 grass in mesic savannas is coupled with the loss of resilience associated with anthropogenic climate change and increased carbon dioxide concentrations. Similarly, increased rainfall events (frequency) are shocks that can overwhelm the arid system, pushing it towards a woody regime.

Changes in the concentration of carbon dioxide provides new research opportunities as savanna dynamics seem to be changing as carbon dioxide concentrations are overriding the historical dynamics of these systems (Buitenwerf, Rose and Higgins, 2015). This reveals a need for new research to investigate the effect of temperature, carbon dioxide concentration on savanna and forest trees; and how this affects tree-grass competition; and hence management policies and strategies.

2.8 REFERENCES

Anadón, J. D. *et al.* (2014) 'Effect of woody-plant encroachment on livestock production in North and South America.', *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences, 111(35), pp. 12948–53. doi: 10.1073/pnas.1320585111.

Angassa, A. and Oba, G. (2009) 'Bush encroachment control demonstrations in southern Ethiopia: 1. Woody species survival strategies with implications for herder land management', *African Journal of Ecology*, 47, pp. 63–76. doi: 10.1111/j.1365-2028.2007.00919.x.

Archibald, S. *et al.* (2009) 'What limits fire? An examination of drivers of burnt area in Southern Africa', *Global Change Biology*, 15, pp. 613–630. doi: 10.1111/j.1365-2486.2008.01754.x.

Archibald, S. (2013) 'African Grazing Lawns: How Fire, Rainfall, and Grazer Numbers Interact to Affect Grass Community States', *The Journal of Wildlife Management*, 72(2), pp. 492–501. doi: 10.2193/2007-045.

Archibald, S., Staver, A. C. and Levin, S. A. (2012) 'Evolution of human-driven fire regimes in Africa.', *Proceedings of the National Academy of Sciences of the United States of America*, 109(3), pp. 847–52. doi: 10.1073/pnas.1118648109.

Van Auken, O. W. (2009) 'Causes and consequences of woody plant encroachment into western North American grasslands.', *Journal of environmental management*, 90(10), pp. 2931–42. doi: 10.1016/j.jenvman.2009.04.023.

Banks, D. I. *et al.* (1996) 'Wood supply and demand around two rural settlements in a semi-arid Savanna, South Africa', *Biomass and Bioenergy*, 11(4), pp. 319–331. doi: 10.1016/0961-9534(96)00031-1.

Bennett, J. E. (2013) 'Institutions and governance of communal rangelands in South Africa', *African Journal of Range & Forage Science*. Taylor & Francis Group , 30(1–2), pp. 77–83. doi: 10.2989/10220119.2013.776634.

Biggs, R. *et al.* (2012) 'Regime Shifts', in Hastings, A; Gross, L. (ed.) *Encyclopedia of Theoretical Ecology*. Ewing, NJ, USA: University of California Press, pp. 609–617.

Biggs, R., Peterson, G. D. and Rocha, J. C. (2018) 'The Regime Shifts Database: a framework for analyzing regime shifts in social-ecological systems', *Ecology and Society*, 23(3), p. art9. doi: 10.5751/ES-10264-230309.

Biggs, R., Schlüter, M. and Schoon, M. L. (2015) *Principles for building resilience : sustaining ecosystem services in social-ecological systems*. Edited by R. Biggs, M. Schlüter, and M. L. Schoon. Cambridge: Cambridge University Press.

Bond, W. J. (2008) 'What Limits Trees in C $_4$ Grasslands and Savannas?', *Annual Review of Ecology, Evolution, and Systematics*, 39(1), pp. 641–659. doi: 10.1146/annurev.ecolsys.39.110707.173411.

Bond, W. J. and Keeley, J. E. (2005) 'Fire as a global " herbivore ": the ecology and evolution of flammable ecosystems', *Trends in Ecology & Evolution*, 20(7), pp. 387–394. doi: 10.1016/j.tree.2005.04.025.

Bond, W. J. and Midgley, G. F. (2000) 'A proposed CO 2 -controlled mechanism of woody plant invasion in grasslands and savannas', *Global Change Biology*, 6, pp. 865–869. doi: 10.1046/j.1365-2486.2000.00365.x.

Bond, W. J. and Midgley, G. F. (2012) 'Carbon dioxide and the uneasy interactions of trees and savannah grasses.', *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 367(1588), pp. 601–12. doi: 10.1098/rstb.2011.0182.

Bond, W. J., Woodward, F. I. and Midgley, G. F. (2005) 'The global distribution of ecosystems in a world without fire', *New Phytologist*, 165(2), pp. 525–538. doi: 10.1111/j.1469-8137.2004.01252.x.

Buitenwerf, R. *et al.* (2012) 'Increased tree densities in South African savannas: >50 years of data suggests CO 2 as a driver', *Global Change Biology*, 18(2), pp. 675–684. doi: 10.1111/j.1365-2486.2011.02561.x.

Buitenwerf, R., Rose, L. and Higgins, S. I. (2015) 'Three decades of multi-dimensional change in global leaf phenology', *Nature Climate Change*, 5(4), pp. 364–368. doi: 10.1038/nclimate2533.

Castley, J. G., Boshoff, A. F. and Kerley, G. I. H. (2001) 'Compromising South Africa's natural biodiversity - Inappropriate herbivore introductions', *South African Journal of Science*, 97(9–10), pp. 344–348.

Chidumayo, E. N. and Gumbo, D. J. (2010) *The dry forests and woodlands of Africa : managing for products and services*. Earthscan. Available at: https://books.google.co.za/books/about/The_Dry_Forests_and_Woodlands_of_Africa.html?id=Idf8wbitYU8C&redir_esc=y (Accessed: 24 July 2017).

Christiaensen, L. and Todo, Y. (2014) 'Poverty Reduction During the Rural–Urban Transformation – The Role of the Missing Middle', *World Development*, 63, pp. 43–58. doi: 10.1016/j.worlddev.2013.10.002.

Christiaensen, L., De Weerdt, J. and Todo, Y. (2013) 'Urbanization and poverty reduction: the role of rural diversification and secondary towns', *Agricultural Economics*, 44(4–5), pp. 435–447. doi: 10.1111/agec.12028.

Crépin, A.-S. *et al.* (2012) 'Regime shifts and management', *Ecological Economics*, 84, pp. 15–22. doi: 10.1016/j.ecolecon.2012.09.003.

Crowlely, G., Garnett, S. and Shepard, S. (2009) 'Impact of storm-burning on Melaleuca viridiflora invasion of grasslands and grassy woodlands on Cape York Peninsula, Australia', *Austral Ecology*. Blackwell Publishing Asia, 34(2), pp. 196–209. doi: 10.1111/j.1442-9993.2008.01921.x.

D'Antonio, C. M. *et al.* (2009) 'Fire in the Earth system', *Science*, 324(5926), p. 481.

Daskin, J. H., Stalmans, M. and Pringle, R. M. (2016) 'Ecological legacies of civil war: 35-year increase in savanna tree cover following wholesale large-mammal declines', *Journal of Ecology*. Edited by L. Gomez-Aparicio, 104(1), pp. 79–89. doi: 10.1111/1365-2745.12483.

Dohn, J. *et al.* (2013) 'Tree effects on grass growth in savannas: competition, facilitation and the stress-gradient hypothesis', *Journal of Ecology*. Edited by R. Callaway, 101(1), pp. 202–209. doi: 10.1111/1365-2745.12010.

Dublin, H. T. (1986) *Decline of the Mara woodlands: the role of fire and elephants [Abstract]*. University of British Columbia.

February, E. and Higgins, S. I. (2013) 'Influence of competition and rainfall manipulation on the growth responses of savanna trees and grasses responses of savanna trees and grasses', *Ecology*, 94(5), pp. 1155–1164. doi: 10.2307/23435957.

Fernandez, R. . *et al.* (2002) 'Degradation and recovery in socio-ecological systems: A view from the household/farm level (PDF Download Available)', in Reynolds, J. . and Stafford Smith, D. . (eds) *Global Desertification: Do humans cause deserts?* Berlin: Dahlem University, pp. 297–323. Available at: https://www.researchgate.net/publication/245856223_Degradation_and_recovery_in_socio-ecological_systems_A_view_from_the_householdfarm_level (Accessed: 27 June 2017).

Folke, C. *et al.* (2004) 'Regime Shifts, Resilience, and Biodiversity in Ecosystem

Management', *Annual Review of Ecology, Evolution, and Systematics*, 35(1), pp. 557–581. doi: 10.1146/annurev.ecolsys.35.021103.105711.

Gray, E. F. and Bond, W. J. (2013) 'Will woody plant encroachment impact the visitor experience and economy of conservation areas?', *Koedoe*, 55(1), pp. 1–9. doi: 10.4102/koedoe.v55i1.1106.

Guldemond, R., Van Aarde, R. and Aarde, R. Van (2008) 'A Meta-Analysis of the Impact of African Elephants on Savanna Vegetation', *Journal of Wildlife Management*. The Wildlife Society, 72(4), pp. 892–899. doi: 10.2193/2007-072.

Hedenus, F., Wirsenius, S. and Johansson, D. J. A. (2014) 'The importance of reduced meat and dairy consumption for meeting stringent climate change targets', *Climatic Change*, 124(1–2), pp. 79–91. doi: 10.1007/s10584-014-1104-5.

Higgins, S. I. *et al.* (2000) 'Fire resprouting and variability a recipe for grass tree coexistence in savanna.pdf', *Journal of Ecology*, 88(2), pp. 213–229.

Higgins, S. I. *et al.* (2007) 'Effects of four decades of fire manipulation on woody vegetation structure in Savanna.', *Ecology*, 88(5), pp. 1119–1125. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17536398 (Accessed: 7 June 2016).

Hoffman, M. T. (2014) 'Changing Patterns of Rural Land Use and Land Cover in South Africa and their Implications for Land Reform', *Journal of Southern African Studies*, 40(4), pp. 707–725. doi: 10.1080/03057070.2014.943525.

Honda, E. A. *et al.* (2016) 'Woody encroachment and its consequences on hydrological processes in the savannah.', *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*. The Royal Society, 371(1703), pp. 115–133. doi: 10.1098/rstb.2015.0313.

Hull, V., Tuanmu, M.-N. and Liu, J. (2015) 'Synthesis of human-nature feedbacks', *Ecology and Society*, 20(3), p. art17. doi: 10.5751/ES-07404-200317.

Jolly, W. M., Nemani, R. and Running, S. W. (2005) 'A generalized, bioclimatic index to predict foliar phenology in response to climate', *Global Change Biology*. Blackwell Science Ltd, 11(4), pp. 619–632. doi: 10.1111/j.1365-2486.2005.00930.x.

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'. doi: 10.1016/j.jaridenv.2008.07.004.

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. doi: 10.1007/s11258-006-9125-4.

Lade, S. J. *et al.* (2015) ‘An empirical model of the Baltic Sea reveals the importance of social dynamics for ecological regime shifts’, *Proceedings of the National Academy of Sciences*, 112(35), pp. 11120–11125. doi: 10.1073/pnas.1504954112.

Van Langevelde, F. *et al.* (2003) ‘EFFECTS OF FIRE AND HERBIVORY ON THE STABILITY OF SAVANNA ECOSYSTEMS’, *Ecology*. Ecological Society of America, 84(2), pp. 337–350. doi: 10.1890/0012-9658(2003)084[0337:EOFAHO]2.0.CO;2.

Leakey, A. D. B. *et al.* (2009) ‘Elevated CO 2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE’, *Journal of Experimental Botany*, 60(10), pp. 2859–2876. doi: 10.1093/jxb/erp096.

Lehmann, C. E. R. *et al.* (2011) ‘Deciphering the distribution of the savanna biome’, *New Phytologist*, 191, pp. 197–209. doi: 10.1111/j.1469-8137.2011.03689.x.

Levin, S. *et al.* (2012) ‘Social-ecological systems as complex adaptive systems: modeling and policy implications’, *Environment and Development Economics*. Cambridge University Press, 18(02), pp. 111–132. doi: 10.1017/S1355770X12000460.

Levin, S. A. (1998) ‘Ecosystems and the Biosphere as Complex Adaptive Systems’, *Ecosystems*, 1(5), pp. 431–436. doi: 10.1007/s100219900037.

Lynam, T. and Brown, K. (2012) ‘Mental Models in Human-Environment Interactions: Theory, Policy Implications, and Methodological Explorations’, *Ecology and Society*. The Resilience Alliance, 17(3), p. art24. doi: 10.5751/ES-04257-170324.

Maciejewski, K. and Kerley, G. I. H. (2014) ‘Understanding tourists’ preference for mammal species in private protected areas: Is there a case for extralimital species for ecotourism?’, *PLoS ONE*, 9(2). doi: 10.1371/journal.pone.0088192.

Madubansi, M. and Shackleton, C. M. (2007) ‘Changes in fuelwood use and selection following electrification in the Bushbuckridge lowveld, South Africa’, *Journal of Environmental Management*, 83(4), pp. 416–426. doi: 10.1016/j.jenvman.2006.03.014.

Meadows, D. (2003) *Thinking in Systems: A Primer*. London: Chelsea Green Publishing. Available at: https://books.google.co.za/books/about/Thinking_in_Systems.html?id=JSgOSP1qklUC&pgis

=1 (Accessed: 1 February 2016).

Meyer, K. M. *et al.* (2007) 'SATCHMO: A spatial simulation model of growth, competition, and mortality in cycling savanna patches', *Ecological Modelling*, 209(2–4), pp. 377–391. doi: 10.1016/j.ecolmodel.2007.07.001.

Millennium Ecosystem Assessment (2005) *Ecosystems and human well-being: synthesis*. Washington, DC.

Moncrieff, G. R. *et al.* (2014) 'Increasing atmospheric CO2 overrides the historical legacy of multiple stable biome states in Africa', *New Phytologist*, 201(3), pp. 908–915. doi: 10.1111/nph.12551.

Nowak, R. S., Ellsworth, D. S. and Smith, S. D. (2004) 'Functional responses of plants to elevated atmospheric CO2- do photosynthetic and productivity data from FACE experiments support early predictions?', *New Phytologist*. Blackwell Science Ltd, 162(2), pp. 253–280. doi: 10.1111/j.1469-8137.2004.01033.x.

O'Connor, T. G. *et al.* (2007) 'A functional hypothesis of the threat of local extirpation of woody plant species by elephant in Africa', *Biological Conservation*, 136(3), pp. 329–345. doi: 10.1016/j.biocon.2006.12.014.

O'Connor, T. G., Puttick, J. R. and Hoffman, M. T. (2014) 'Bush encroachment in southern Africa : changes and causes', *African Journal of Range and Forage Science*, 31(October), pp. 67–88. doi: 10.2989/10220119.2014.939996.

Polley, H. W. (1997) 'Implications of rising atmospheric carbon dioxide concentration for rangelands', *Journal of Range Management*, 50(6), pp. 562–577. doi: 10.2307/4003450.

Ratnam, J. *et al.* (2011) 'When is a "forest" a savanna, and why does it matter?', *Global Ecology and Biogeography*, 20(5), pp. 653–660. doi: 10.1111/j.1466-8238.2010.00634.x.

Reyers, B. *et al.* (2013) 'Getting the measure of ecosystem services: a social–ecological approach', *Frontiers in Ecology and the Environment*. Ecological Society of America, 11(5), pp. 268–273. doi: 10.1890/120144.

Rietkerk, M. *et al.* (2004) 'Self-organized patchiness and catastrophic shifts in ecosystems.', *Science (New York, N.Y.)*, 305(5692), pp. 1926–9. doi: 10.1126/science.1101867.

Roques, K. G. G., O'Connor, T. G. G. and Watkinson, A. R. 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. doi: 10.1046/j.1365-2664.2001.00567.x.

Sage, R. F. (2004) 'The evolution of C 4 photosynthesis', *New Phytologist*, 161, pp. 341–370. doi: 10.1046/j.1469-8137.2004.00974.x.

Sankaran, M. *et al.* (2005) 'Determinants of woody cover in African savannas.', *Nature*, 438(7069), pp. 846–9. doi: 10.1038/nature04070.

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. doi: 10.1111/j.1466-8238.2007.00360.x.

Sankaran, M., Ratnam, J. and Hanan, N. P. (2004) 'Tree-grass coexistence in savannas revisited - Insights from an examination of assumptions and mechanisms invoked in existing models', *Ecology Letters*, 7(6), pp. 480–490. doi: 10.1111/j.1461-0248.2004.00596.x.

Scheffer, M. *et al.* (2001) 'Catastrophic shifts in ecosystems.', *Nature*, 413(6856), pp. 591–596. doi: 10.1038/35098000.

Scholes, R. J. (2003) 'Convex Relationships in Ecosystems Containing Mixtures of Trees and Grass', *Environmental and Resource Economics*, 26(4), pp. 559–574. doi: 10.1023/B:EARE.0000007349.67564.b3.

Scholes, R. J. and Archer, S. R. (1997) 'Tree Grass Interactions in Savannas', *Annual Review of Ecology and Systematics*, pp. 517–544. doi: 0066-4162/97/1120-0517.

Shackleton, C. *et al.* (2005) 'The contribution and direct-use value of livestock to rural livelihoods in the Sand River catchment, South Africa', *African Journal of Range & Forage Science*. Taylor & Francis Group , 22(2), pp. 127–140. doi: 10.2989/10220110509485870.

Shackleton, R. *et al.* (2013) 'Deagrarianisation and forest revegetation in a biodiversity hotspot on the Wild Coast, South Africa.', *PloS one*, 8(10), p. e76939. doi: 10.1371/journal.pone.0076939.

Skarpe, C. (1990) 'Shrub Layer Dynamics Under Different Herbivore Densities in an Arid Savanna, Botswana', *Journal of Applied Ecology*, 27(3), pp. 873–885. doi: 10.2307/2404383.

Skowno, A. L. *et al.* (2017) 'Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers', *Global Change Biology*, 23(6), pp. 2358–2369. doi: 10.1111/gcb.13529.

Smit, G. . N. (2004) 'An approach to tree thinning to structure southern African savannas for long-term restoration from bush encroachment.', *Journal of environmental management*, 71(2), pp. 179–91. doi: 10.1016/j.jenvman.2004.02.005.

Smit, I. P. J. *et al.* (2016) 'An examination of the potential efficacy of high-intensity fires for reversing woody encroachment in savannas', *Journal of Applied Ecology*, 53(5), pp. 1623–1633. doi: 10.1111/1365-2664.12738.

Staver, A. C., Archibald, S. and Levin, S. (2011) 'Tree cover in sub-Saharan Africa: Rainfall and fire constrain forest and savanna as alternative stable states', *Ecology*, 92(5), pp. 1063–1072. doi: 10.1890/i0012-9658-92-5-1063.

Staver, A. C., Archibald, S. and Levin, S. a. (2011) 'The global extent and determinants of savanna and forest as alternative biome states.', *Science (New York, N.Y.)*, 334(6053), pp. 230–2. doi: 10.1126/science.1210465.

Staver, A. C. *et al.* (2009) 'Browsing and fire interact to suppress tree density in an African savanna', *Ecological Applications*. Ecological Society of America, 19(7), pp. 1909–1919. doi: 10.1890/08-1907.1.

Staver, A. C. and Bond, W. J. (2014) 'Is there a "browse trap"? Dynamics of herbivore impacts on trees and grasses in an African savanna', *Journal of Ecology*. Edited by A. Austin, 102(3), pp. 595–602. doi: 10.1111/1365-2745.12230.

Stevens, N. *et al.* (2014) 'Increasing temperatures can improve seedling establishment in arid-adapted savanna trees', *Oecologia*, 175(3), pp. 1029–1040. doi: 10.1007/s00442-014-2958-y.

Stevens, N. *et al.* (2016) 'Woody encroachment over 70 years in South African savannahs: overgrazing, global change or extinction aftershock?', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1703), p. 20150437. doi: 10.1098/rstb.2015.0437.

Tedder, M. *et al.* (2014) 'Tree-grass competition along a catenal gradient in a mesic grassland, South Africa', *Grassland Science*, 60(1), pp. 1–8. doi: 10.1111/grs.12034.

Twidwell, D. *et al.* (2013) 'Refining thresholds in coupled fire-vegetation models to improve management of encroaching woody plants in grasslands', *Journal of Applied Ecology*. Edited by P. Kardol, 50(3), pp. 603–613. doi: 10.1111/1365-2664.12063.

Vadigi, S. and Ward, D. (2014) 'Herbivory effects on saplings are influenced by nutrients and grass competition in a humid South African savanna', *Perspectives in Plant Ecology, Evolution and Systematics*, 16(1), pp. 11–20. doi: 10.1016/j.ppees.2013.10.002.

Walker, B. *et al.* (2004) 'Resilience, Adaptability and Transformability in Social – ecological Systems', *Ecology and Society*, 9(2), p. 5. doi: 10.1103/PhysRevLett.95.258101.

Ward, D. (2005) 'Do we understand the causes of bush encroachment in African savannas?', *African Journal of Range & Forage Science*, 22(2), pp. 101–105. doi: 10.2989/10220110509485867.

Ward, D. and Esler, K. J. (2011) 'What are the effects of substrate and grass removal on recruitment of *Acacia mellifera* seedlings in a semi-arid environment?', *Plant Ecology*. Springer Netherlands, 212(2), pp. 245–250. doi: 10.1007/s11258-010-9818-6.

Ward, D., Wiegand, K. and Getzin, S. (2013) 'Walter's two-layer hypothesis revisited: back to the roots!', *Oecologia*, 172(3), pp. 617–30. doi: 10.1007/s00442-012-2538-y.

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. doi: 10.1016/j.ppees.2005.10.001.

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. doi: 10.1111/j.1365-2028.2008.01051.x.

Wigley, B. J., Bond, W. J. and Hoffman, M. T. (2010) 'Thicket expansion in a South African savanna under divergent land use: Local vs. global drivers?', *Global Change Biology*, 16(3), pp. 964–976. doi: 10.1111/j.1365-2486.2009.02030.x.

van Wilgen, B. W. *et al.* (2010) 'Fire management in Mediterranean-climate shrublands: A case study from the Cape fynbos, South Africa', *Journal of Applied Ecology*, 47(3), pp. 631–638. doi: 10.1111/j.1365-2664.2010.01800.x.

CHAPTER 3: USING REMOTELY SENSED LANDSAT IMAGERY TO MONITOR WOODY ENCROACHMENT IN A SOUTH AFRICAN SAVANNA UNDER CONTRASTING LAND USE PRACTICES

This chapter is intended for submission in African Journal of Range and Forage Science as: Luvuno, LB; Biggs, R; Stevens, N; Esler, K, Luck-Vogel, M. Using remotely sensed LANDSAT imagery to monitor woody encroachment in a South African savanna under contrasting land use practices

3.1 ABSTRACT

Savannas worldwide are undergoing woody encroachment which has significant economic, cultural and ecological implications. There are a plethora of studies trying to understand the phenomenon and identify key drivers of increased woody cover, which range from global to local drivers. In this study we perform a time series analysis using Landsat TM imagery to quantify and monitor the extent of woody encroachment from 1990 to 2016 in Hlabisa, South Africa. Hlabisa consists of areas with contrasting land use practices, primarily comprising of a state-run conservation area and communal lands with subsistence agriculture. The analyses showed highly significant increases in tree cover across all land uses between the 1990 and 2016, with land use practice impacting the extent and rate of increase in woody cover. Total tree cover increased from 29% in 1990 to 52% in 2016 in the conservation areas and from 17 to 35% in the communal areas. Our results suggest global drivers, likely increased CO_2, is favouring woody encroachment in savannas regardless of land use practises.

Keywords: *Remote sensing; savannas; change detection; woody encroachment; Landsat imagery*

3.2 INTRODUCTION

The savanna biome covers approximately 25% of the earth's surface, is home to a fifth of the earth's population and supports 50% of the planet's livestock (Scholes and Archer, 1997; Millennium Ecosystem Assessment, 2005; Briske, 2017a). Savannas provide a wide range of ecosystem services from provisioning services such as livestock grazing and fuelwood, to supporting and regulating services such as biodiversity and carbon sequestration, as well as a variety of cultural services (Briske, 2017b). The ability of savannas to provide several key services is dependent on the persistence of a grassy savanna regime which is characterised by a continuous grass layer and a discontinuous tree layer (Ratnam *et al.*, 2011). This grassy regime is however threatened by woody encroachment, a shift from a grassy savanna to a persistently woody savanna, which typically involves indigenous woody species (Bond and Midgley, 2012).

Savannas worldwide are undergoing woody encroachment (Stevens, Lehmann, *et al.*, 2017), and there are a plethora of studies trying to understand the phenomenon. Conflicting theories regarding the causes of increased woody cover exist and are still being debated. These theories vary between global drivers (e.g. increased concentration of carbon dioxide in the atmosphere and climate change; Bond and Midgley, 2012; Buitenwerf, Bond, Stevens and Trollope, 2012) and local drivers (e.g. overgrazing and fire manipulation; Hoffman and O'Connor, 1999; Bond and Keeley, 2005; Sankaran *et al.*, 2005; Staver and Bond, 2014). Woody encroachment often entails a regime shift – a change in the structure and function of the ecosystem - that occurs as result of the interaction of both global and local ecological drivers, as well as various underlying social processes such as urbanization and land use change (D'Odorico, Okin, and Bestelmeyer 2012; Ratajczak, Nippert, and Ocheltree 2014; Luvuno *et al.*, 2018; Chapter 2).

The majority of people residing in savannas are located in developing countries, which makes them particularly vulnerable to the effects of woody encroachment as they are more reliant on natural resources from these systems (Cumming *et al.*, 2014; Briske, 2017a). In southern Africa, woody encroachment has been a problem for nearly a century (O'Connor, Puttick and Hoffman, 2014). In 1989, an estimated 13 million hectares of savanna were affected by woody encroachment in South Africa (Eldridge *et al.*, 2011). In a recent study, Skowno et al. (2017) estimated a further 2.7 million ha have become encroached occurred South Africa since 1990, with savannas receiving >500 mm mean annual precipitation (MAP) showing higher rates of woody encroachment than regions receiving <500 mm (Skowno *et al.*, 2017). Multiple studies have also found that land use has a significant effect on the rate of woody encroachment (Hoffman and O'Connor, 1999; Wigley, Bond and Hoffman, 2009; Skowno *et al.*, 2017).

With the increasing prevalence of woody encroachment and its impacts across savannas worldwide, there is a growing need for cost-effective techniques to better assess woody encroachment over large scales. There is also a need to better understand the different drivers of woody encroachment and how they interact at different scales. Conventionally, the study of woody encroachment involves a combination of fieldwork and aerial photography (Higgins, Shackleton and Robinson, 1999; Wigley, Bond and Hoffman, 2009; Puttick, Hoffman and Gambiza, 2011; Ward, Hoffman and Collocott, 2014; Stevens *et al.*, 2016). Most of the remote sensing studies on woody encroachment in southern Africa have used historical photographs (both aerial and oblique) covering only small geographic areas (Puttick, Hoffman and Gambiza, 2011; Rohde and Hoffman, 2012; Russell and Ward, 2014; Stevens *et al.*, 2016). There are advantages to using aerial imagery – the high spatial resolution provides a more accurate assessment of woody encroachment. However, these methods are labour intensive and limit the ability to monitor woody encroachment and understand savanna dynamics at larger scales.

Satellite derived remote sensing data provides the possibility to map woody encroachment over larger spatial areas, and investigate the drivers and dynamics of change at varying spatial scales (Coppin *et al.*, 2004). The main challenge with using remote sensing data is that annual variability in vegetation growth in response to variable rainfall patterns (i.e., phenology changes) obscures the encroachment processes. To identify areas where observed changes were not likely to be phenology-driven, analyses need to be aided by long term precipitation data (Lück-Vogel and Strohbach, 2009).

In this study we use Landsat TM imagery to test an approach to larger-scale mapping and quantification of woody encroachment. We quantify the extent of woody encroachment in the Hlabisa region of South Africa over a period of 26 years. This area has undergone substantial woody encroachment in the last 20 years and provides a good case study for testing the approach (Wigley, Bond and Hoffman, 2009). Secondly, we quantify and compare woody encroachment across two land use practices – a state-owned conservation area with mega-herbivores, and communal areas that comprise mainly of small-scale subsistence farming - to get an understanding of the impact different land use practices have on woody encroachment. We relate our findings to long-term precipitation data for the area to account for climate-driven changes.

3.3 MATERIALS AND METHODS

3.3.1 Study Area Description

The study was undertaken in the Hlabisa district of KwaZulu-Natal, South Africa (28.00°S to 28.25°S and 32.00°E to 32.58°E) (Figure 3.1). The mean annual precipitation (MAP) of the area ranges from 700 mm - 990 mm per annum, with most of the rainfall falling in the summer months of September to March. Temperatures in the area are warm to hot, particularly during the summer months. Mean annual temperature in the region is 22.5°C with a mean minimum July temperature of 13°C and a mean maximum February temperature of 35°C (Wigley, Bond and Hoffman, 2009). The study area falls predominantly into Northern Zululand Sourveld (SVI 22) with some Zululand Lowveld (SVI 23) and patches of Scarp Forest (FOz5) (Mucina and Rutherford, 2006). Soils are mainly derived from Karoo sediments (shales, mudstones, sandstones) interspersed with dolerite intrusions producing clay-rich soils (Wigley, Bond and Hoffman, 2009).

Land use in the study area comprises of communal lands (33%) and a state conservation area (Hluhluwe-imfolozi Park) (38%), which have different management practices. Communal lands are areas that have been utilized by rural communities for centuries (Higgins *et al*., 1999), and still operate under traditional tenure arrangements. The state conservation area was established in 1895 and is managed by a provincial conservation agency. Hluhluwe- imfolozi Park has had low grazer numbers over the past century compared to the communal areas. However, a change occurred in 1990 when a substantial number of mixed feeder browsers were introduced into the park (Wigley, Bond and Hoffman, 2010). Wood harvesting is higher in the communal areas (Wigley, Bond and Hoffman, 2009).The use of fire also differs between these areas. Communal areas have had a fire regime characterised by frequent, less intense fires compared to the conservation area, which has more frequent and hotter fires (Wigley, Bond and Hoffman, 2009; Case and Staver, 2017).

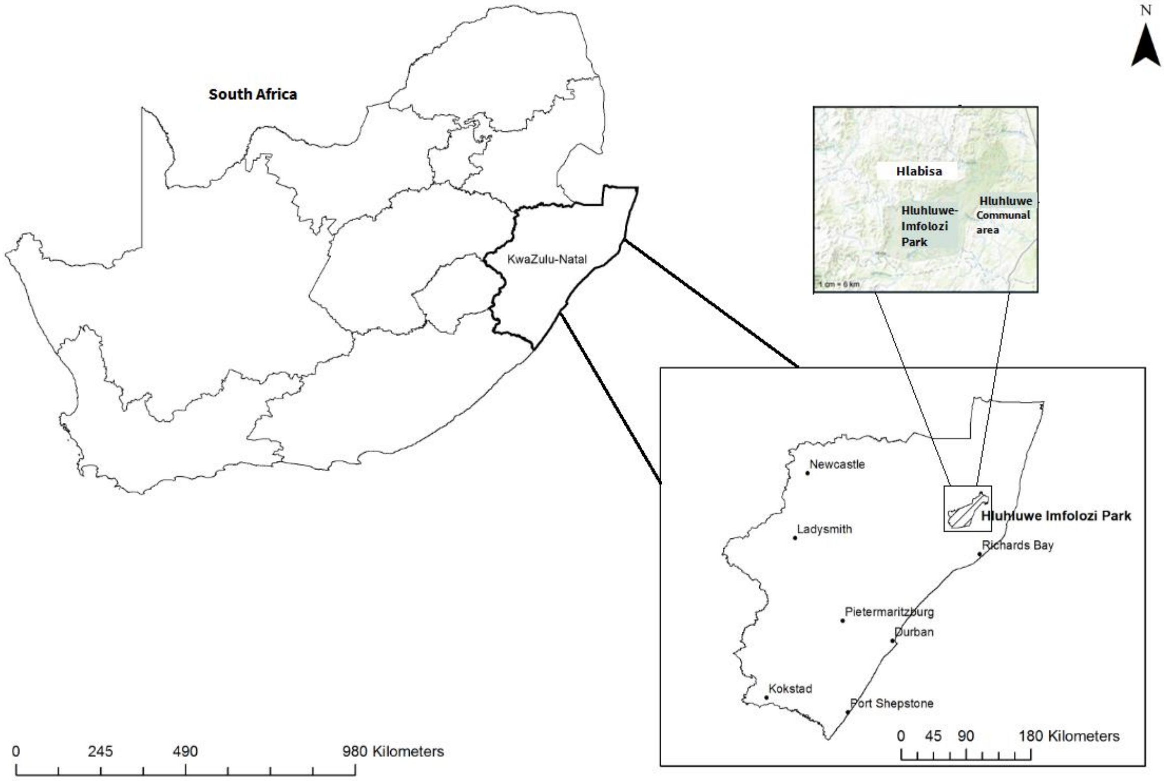

Figure 3.1: Study site location: the Hlabisa district in Zululand.

3.3.2 Image processing and classification

To quantify the extent of woody encroachment in Hlabisa we performed land cover classifications using Landsat images spanning the period from 1990 to 2016 (Table 3.1). Woody encroachment was cited to have started in the early 2000s in the area so we chose this period to monitor changes prior to the change. The Landsat images were obtained from the United States Geologiical Survey (USGS) and included both Landsat 5 and Landsat 8 images, with a resolution of 30 m x 30 m. Images were chosen on the basis of season and rainfall history to ensure that the observed changes in woody cover were not phenology driven – i.e., seasonal changes in vegetation structure based on climatic factors, especially rainfall. We chose one image per year taken at the end of the rainy season and a few weeks after at least 200 mm of rainfall. We obtained eleven cloud free images of the appropriate timing, covering the years 1990-2016 (Table 3.1). Radiometric correction was done to correct for sensor and atmospheric variation in the images using Atcor 2 embedded in the IDL, 8.2 software (Harris Geospatial Solutions, USA). Radiometric correction has been shown to significantly improve the accuracy and transferability of image classification results (Richter and Schlapfer, 2016).

The corrected images were imported into ArcGIS 10.3 (Esri, California, USA), clipped to the study area boundary and masked using the national land cover map (NLC 2000) to remove transformed areas (urban areas and commercial agriculture sites) which interfered with the effectiveness of the land cover classification technique. The clipped images were then imported into Erdas Imagine 2016 (Hexagon Geospatial, Alabama, USA) for classification. Four land cover classes (trees, grass, bare soil and water) were used. Slope areas covered in trees were often mistaken for water, and a slope class was created to remove this error. After the classification, a visual desktop accuracy assessment was done to ensure the method was working. A minimum of 25 spectral signatures were collected on each image for each class. A supervised classification was then done on the images using the maximum likelihood classifier. Once the images were classified, tree and grass cover percentages were calculated for the study area. The images were then imported back into ArcGIS to calculate tree and grass cover percentages for each land use. A chi-squared test was then done to test if there were significant differences in tree cover between 1990-2006 and 2009-2016.

Table 3. 1: Summary of the data used in the analysis

Acquisition Date	Sensor, Source of Data	Bands
1990	Landsat 5 TM, USGS	7
1991	Landsat 5 TM, USGS	7
1995	Landsat 5 TM, USGS	7
1996	Landsat 5 TM, USGS	7
1998	Landsat 5 TM, USGS	7
1999	Landsat 5 TM, USGS	7
2001	Landsat 5 TM, USGS	7
2006	Landsat 5 TM, USGS	7
2009	Landsat 5 TM, USGS	7
2011	Landsat 5 TM, USGS	7
2016	Landsat 8, USGS	11

3.3.3 Accuracy assessment

To determine classification accuracy, 200 random sample points per class were created and distributed across the classification, saved as a KML file and imported into Google Earth to collect reference data. A confusion matrix was then created with the reference data to calculate the accuracy of the classification. An accuracy assessment was carried out for only one of the images since the methodology was standard across all the images, an approach that is commonly utilised (Brandt and Townsend, 2006; Munyati, Shaker and Phasha, 2011).

3.3.4 Precipitation data

We tested the extent to which variation in rainfall explained the observed changes in woody cover. Rainfall data spanning our study period was extracted from park records. These were from seven rainfall gauges situated in different sections of the park. We used these records because the national weather service only had one rainfall gauge for the entire area. We assumed that the rainfall in the park is representative of the rainfall in the communal lands surrounding the park.

3.4 RESULTS

3.4.1 Woody encroachment in Hlabisa

Grass was the dominant vegetation type in the area from 1990 to 2006 (Figure 3.2). In 1990, grass covered 51% of the study area, and fluctuated between 40% and 50% for the next 15 years. In 2009, a substantial drop in grass cover to 34% of the study area occurred. Grass cover has subsequently remained at this lower level, with 30% cover recorded in 2011 and 32% in 2016. Trees covered 17% of the study area in 1990, and fluctuated between 19% and 26% until 2006. After 2009, higher tree covers, fluctuating between 32% and 35% of the study area were found.

Tree cover percentage is statistically different between 1990-2006 and 2009-2016 ($p > 0.001$, $t = -12.955$). The peak increase in tree cover occurred from 2009 to 2016 with an acceleration rate of around 1% per year (Figure 3.3).

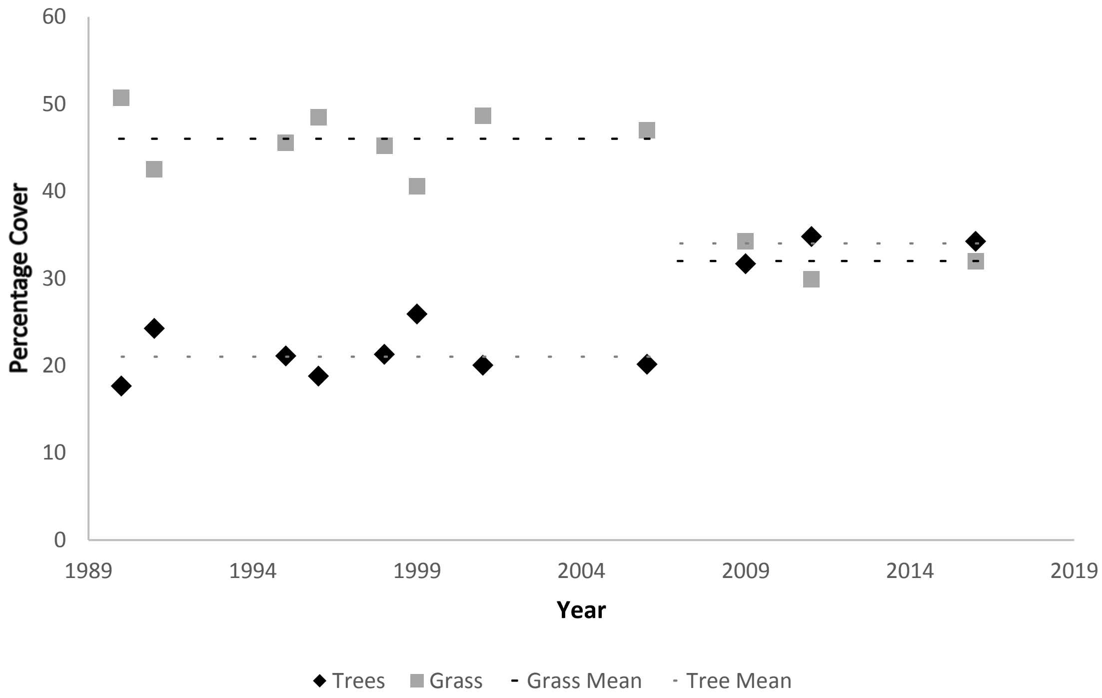

Figure 3.2: Tree and grass cover in Hlabisa over time. *Dashed lines represent the average cover for 1990-2006, and 2009-2016.*

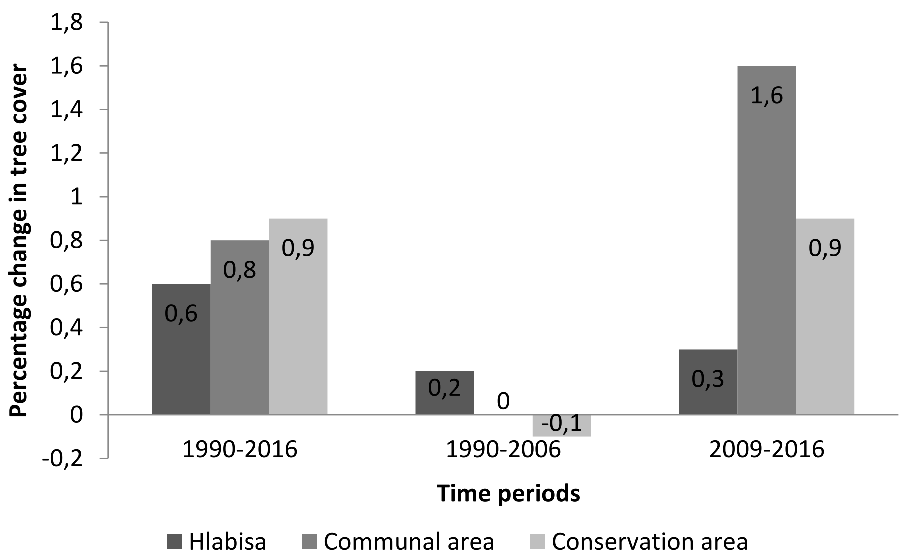

Figure 3.3: Annual change in tree cover per land use practice. *Hlabisa is the whole study area, comprising of 33% communal areas and 38% conservation areas.*

3.4.2 Woody encroachment across land use

The largest tree cover changes have occurred in conservation areas (Figure 3.4). Trees covered 28% of the conservation area in 1990, nearly doubling by 2016 to cover 52%. This represents an 81% increase in tree cover over 26 years with an average rate of 0.9% change per year (Figure 3.3). Tree cover in the communal areas has also doubled from 17% in 1990 to 36% in 2016. The rate of change in communal areas is currently at its highest, at an alarming 1.6 % change per year compared to 0% change per year from 1990-2006 (Figure 3.3).

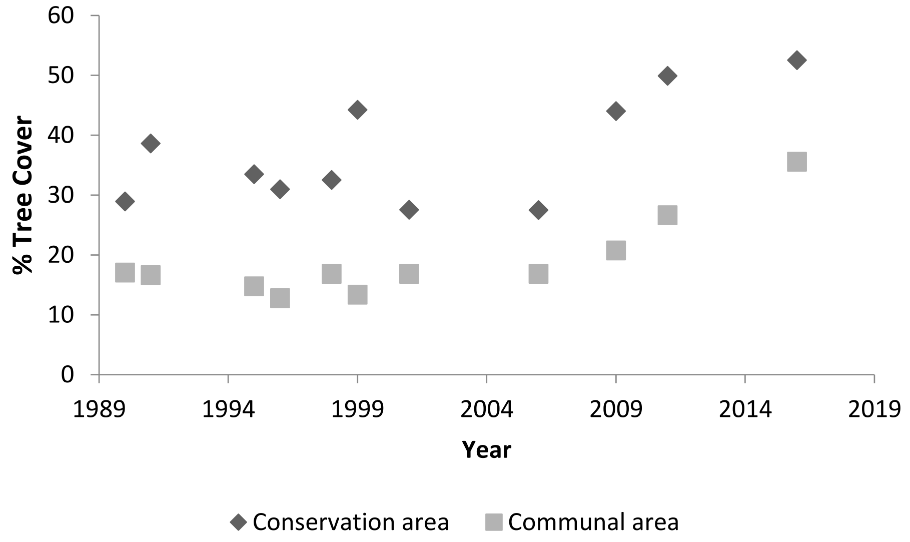

Figure 3.4: Changes in plant cover in the across the land use types.

3.4.3 Changes in precipitation

While tree cover has increased over time, the mean annual rainfall in the area has declined (Figure 3.5). The average MAP in the area from 1990-2006 was 726.9 mm, which dropped to 583.1 mm from 2009-2016 ($p = 0.007$, $t = 2.74$).

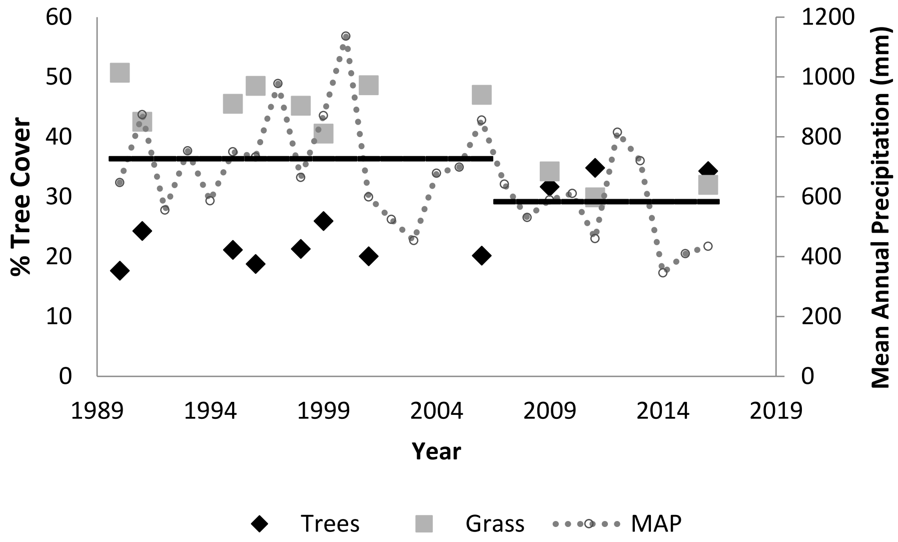

Figure 3.5: Vegetation cover and mean annual precipitation in Hlabisa over time. *The black lines represent the average MAP over the two time periods.*

3.4.4 Accuracy assessment

The overall accuracy of our classification was ~75%.

Table 3. 2: Accuracy assessment matrix

		Reference Data			
		Trees	Grass	Other	Totals
Classified	Trees	185	52	1	238
	Grass	43	136	18	197
	Other	4	34	127	165
	Totals	232	222	146	600

	Producer's Accuracy	User's Accuracy
Trees	79,74	77,73
Grass	61,26	69,04
Other	86,99	76,97
Kappa	0,65	
Overall	74,67	

3.5 Discussion

In this study, we trialled the use of Landsat imagery as a tool for monitoring and quantifying the extent of woody encroachment across large spatial areas. This study expands on previous studies that have piloted the use of hyperspectral remote sensing imagery for monitoring woody encroachment (Wigley, Bond and Hoffman, 2009; Russell and Ward, 2013; Ward, Hoffman and Collocott, 2014; Stevens *et al.*, 2016; Skowno *et al.*, 2017), but in this study we use readily available multispectral imagery to quantify the extent of woody encroachment without the aid of any ancillary hyperspectral imagery. We focused specifically on the Hlabisa area of South Africa and compared woody encroachment across two land use practices, as well as considering the effect of rainfall.

The results of our study demonstrate the potential for using multispectral remote sensing data for monitoring, detecting and quantifying woody encroachment. Results demonstrate widespread increases in woody vegetation across Hlabisa, under both the conservation and communal subsistence farming land uses. Our findings concur with previous studies in the area (Wigley, Bond and Hoffman, 2009; Case and Staver, 2017) as well as reports of widespread increases of woody vegetation within South Africa (Russell and Ward, 2014; Symeonakis and Higginbottom, 2014; Stevens *et al.*, 2016; Skowno *et al.*, 2017) and in savannas globally (Stevens, Lehmann, *et al.*, 2017). Using free and readily available Landsat imagery to quantify and monitor woody encroachment in Hlabisa therefore yielded similar estimates as studies that used aerial imagery and satellite images with high spatial resolutions (Hoffman and O'Connor, 1999; Wigley, Bond and Hoffman, 2009; Munyati, Shaker and Phasha, 2011; Stevens *et al.*, 2016).

The overall accuracy of our classification was 75%, which we suggest is acceptable for many purposes. Higher resolution datasets such as aerial images and hyperspectral imagery generally have higher accuracy levels, but generally entail significant financial costs, and are limited in their spatial extent. Most of the world's savannas are in developing countries and access to high resolution imagery can be a significant obstacle to the monitoring and sustainable management of savannas. Landsat data are freely available, but the coarser resolution means that many of the random accuracy assessment points fall on mixed pixels that are difficult to assign to one class or another, leading to a lower accuracy. Compared to other studies with this resolution of data, 75% accuracy is commendable. Other studies have produced accuracies varying from 75-91% depending on the model used and whether the Landsat data were paired with ancillary data with high spatial resolution (Lück-Vogel and Strohbach, 2009; Munyati, Shaker and Phasha, 2011; Symeonakis and Higginbottom, 2014). We suggest that good accuracy levels in this study were attained through careful radiometric corrections and image selection based on detailed rainfall data to avoid phenology effects. This would be important for similar applications in other areas.

Overall, we found that woody encroachment in Hlabisa is more prevalent in the conservation areas, where the rate of tree cover change is also greater. This concurs with findings by Wigley, Bond and Hoffman, (2009) who reported land use to have enormous impacts on woody encroachment in the Hluhluwe area, with community areas having the lowest percentage change and the conservation area having the highest change. Hluhluwe is part of the Hlabisa district of South Africa, with a MAP >700 mm and therefore particularly vulnerable to woody encroachment and canopy closure (Sankaran *et al.*, 2005). In contrast, other studies have found conservation areas with elephants to have low rates woody encroachment or in some cases decreased rates of encroachment (Stevens *et al.*, 2016; Skowno *et al.*, 2017). We found tree cover increased by 81% in the conservation area, suggesting that there are factors overpowering the ability of elephants to minimize woody encroachment. However, when examining the rate of change by decade (Figure 3.3), the conservation area currently has a lower rate of woody encroachment than the communal areas. According to Case and Staver (2017), certain areas of the park have recently (2007-2014) experienced higher than historic fire frequencies which seem to have slowed woody encroachment.

Although the communal areas have typically experienced lower rates of encroachment (Wigley, Bond and Hoffman, 2010; Stevens *et al.*, 2016; Skowno *et al.*, 2017), the rate of encroachment is currently almost twice that of the conservation area. Tree harvesting and high stocking rates were cited as the reason for low rates of woody encroachment in communal areas in the past (Wigley, Bond and Hoffman, 2009). More recently, Russell and Ward (2014) suggested that declining fuelwood collection (due to increased electrification of rural areas) may be contributing to woodland expansion in rural savannas of South Africa. According to the South Africa census in 2011, 54% of the Hlabisa area had electricity compared to the 32% in 2001 (StatsSA 2018). Eskom, the national electricity provider, electrified 40 000 households in 2016 alone in the Hlabisa district (www.eskom.com). Electrification therefore potentially explains the recent increased rates of encroachment in communal areas. Another land use practice change that may have contributed to the current high rate of encroachment is the abandonment of crop farming. Deagrarianisation and abandonment of cultivated fields in large parts of South African communal areas has been linked to a significant increase in woody encroachment (Shackleton *et al.*, 2013; Hoffman, 2014).

We further found that the increase in woody encroachment in Hlabisa may be linked to a reduction in the MAP since 2001. Droughts have been found to have profound impacts on woody encroachment in mesic savannas through the reduction of grass and therefore fire (Kraaij and Ward, 2006; Joubert, Rothauge and Smit, 2008; O'Connor, Puttick and Hoffman, 2014; Nackley *et al.*, 2018). In mesic savannas, such as those found in the Hlabisa area, increased soil moisture contributes to increased grass biomass, which leads to higher levels of grass competition, higher fuel loads and fire intensities (Sankaran *et al.*, 2005; Sankaran, Ratnam and Hanan, 2008; Van Auken, 2009; Vadigi and Ward, 2014). Fire in turn prevents canopy closure in mesic savanna, as trees are unable to establish because the seedlings and saplings are constantly knocked back by herbivory and fire (Higgins *et al.*, 2000). An extreme drought reduces grass biomass and when rain does arrive, grass recovery is slow (Wiegand, Saltz and Ward, 2006). It is usually during this time that tree establishment can occur in the absence of grass competition (Kraaij and Ward, 2006; O'Connor, Puttick and Hoffman, 2014). This appears to have been the case in Hlabisa since the early 2000s, particularly in the conservation area (Figure 3.4). High tree usage in the communal areas likely prevented accelerated encroachment in those areas until more recently (Wigley, Bond and Hoffman, 2009). In contrast, reduced rainfall over the past decade may have contributed to deagrarianisation in the community areas, in addition to likely reducing fire frequency and intensity.

Our results highlight that woody encroachment is increasing in the Hlabisa area regardless of land use and disturbance processes. This mirrors results elsewhere (Stevens, Lehmann, *et al.*, 2017; Venter, Cramer and Hawkins, 2018), and suggests that global drivers, rather than differences in local management practices, are driving encroachment. Several global drivers of woody encroachment have been proposed, with increasing carbon dioxide (CO2) concentration gaining increasing consensus (Wigley, Bond and Hoffman, 2010; O'Connor, Puttick and Hoffman, 2014; Stevens *et al.*, 2016; Case and Staver, 2017; Skowno *et al.*, 2017). This is supported by evidence from multiple Free-Air Carbon Dioxide Enrichment (FACE) experiments which expose vegetation to elevated CO2 (Leakey *et al.*, 2009). The hypothesis in mesic savannas is that higher carbon dioxide concentration levels favour C3 (woody plant) photosynthesis relative to C4 (tropical grass) photosynthesis which accelerates woody plant growth and can prevent saplings from being knocked back by fire (Polley, 1997; Buitenwerf, Bond, Stevens and Trollope, 2012). These changes may be accelerating the effects of the deagrarianisation, reduced fuelwood harvesting, drought and reduced fire in Hlabisa. All these drivers contribute to either the establishment or persistence of woody encroachment.

Increases in woody encroachment have been linked to various impacts on ecosystem services (Eldridge et al. 2011; Chapter 5). Continued encroachment in Hlabisa is likely to have significant impacts on the local land users. Monitoring of changes in encroachment could help inform management actions to reduce levels of encroachment and safeguard local livelihoods. This study suggests that Landsat is a potential cost-effective way of monitoring changes in woody encroachment on an ongoing basis.

3.6 CONCLUSION

The results of this study provide support for the use of multispectral satellite-based remote sensing data to monitor and assess woody encroachment, provided careful radiometric corrections are done and images are selected to minimize phenology effects. We found that encroachment occurred across the Hlabisa area, regardless of land use practice, with woody cover doubling between 1990 and 2016. Over the 26-year study period, the conservation area has had a slightly higher rate of encroachment, but the rate of change in the communal area currently exceeds that of the conservation area, possibly due electrification of the area which has reduced tree harvesting rates. The findings of this study suggest that land use practices, regional and global drivers are likely interacting to drive woody encroachment in the study area.

3.7 References

Van Auken, O. W. (2009) 'Causes and consequences of woody plant encroachment into western North American grasslands.', *Journal of environmental management*, 90(10), pp. 2931–42. doi: 10.1016/j.jenvman.2009.04.023.

Bond, W. J. and Keeley, J. E. (2005) 'Fire as a global " herbivore ": the ecology and evolution of flammable ecosystems', *Trends in Ecology & Evolution*, 20(7), pp. 387–394. doi: 10.1016/j.tree.2005.04.025.

Bond, W. J. and Midgley, G. F. (2012) 'Carbon dioxide and the uneasy interactions of trees and savannah grasses.', *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 367(1588), pp. 601–12. doi: 10.1098/rstb.2011.0182.

Brandt, J. S. and Townsend, P. A. (2006) 'Land use - Land cover conversion, regeneration and degradation in the high elevation Bolivian Andes', *Landscape Ecology*, 21(4), pp. 607–623. doi: 10.1007/s10980-005-4120-z.

Briske, D. D. (2017a) 'Rangeland Systems: Foundation for a Conceptual Framework', in, pp. 1–21. doi: 10.1007/978-3-319-46709-2_1.

Briske, D. D. (ed.) (2017b) *Rangeland Systems*. Cham: Springer International Publishing (Springer Series on Environmental Management). doi: 10.1007/978-3-319-46709-2.

Buitenwerf, R. *et al.* (2012) 'Increased tree densities in South African savannas: >50 years of data suggests CO 2 as a driver', *Global Change Biology*, 18(2), pp. 675–684. doi: 10.1111/j.1365-2486.2011.02561.x.

Case, M. F. and Staver, A. C. (2017) 'Fire prevents woody encroachment only at higher-than-historical frequencies in a South African savanna', *Journal of Applied Ecology*, 54(3), pp. 955–962. doi: 10.1111/1365-2664.12805.

Coppin, P. *et al.* (2004) 'Review ArticleDigital change detection methods in ecosystem monitoring: a review', *International Journal of Remote Sensing*. Taylor & Francis Group , 25(9), pp. 1565–1596. doi: 10.1080/0143116031000101675.

Cumming, G. S. *et al.* (2014) 'Implications of agricultural transitions and urbanization for ecosystem services', *Nature*, 515(7525), pp. 50–57. doi: 10.1038/nature13945.

D'Odorico, P., Okin, G. S. and Bestelmeyer, B. T. (2012) 'A synthetic review of feedbacks and drivers of shrub encroachment in arid grasslands', *Ecohydrology*, 5(October 2011), pp.

520–530. doi: 10.1002/eco.259.

Eldridge, D. J. *et al.* (2011) 'Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis.', *Ecology letters*, 14(7), pp. 709–22. doi: 10.1111/j.1461-0248.2011.01630.x.

Higgins, S. I. *et al.* (2000) 'Fire resprouting and variability a recipe for grass tree coexistence in savanna.pdf', *Journal of Ecology*, 88(2), pp. 213–229.

Higgins, S. I., Shackleton, C. M. and Robinson, E. R. (1999) 'Changes in Woody Community Structure and Composition under Contrasting Landuse Systems in a Semi', *Journal of Biogeography*, 26(3), pp. 619–627. Available at: https://www.jstor.org/stable/pdf/2656147.pdf?refreqid=excelsior%3A79b3410e731dd3505e9d58ff224af70e (Accessed: 29 November 2018).

Hoffman, M. T. (2014) 'Changing Patterns of Rural Land Use and Land Cover in South Africa and their Implications for Land Reform', *Journal of Southern African Studies*, 40(4), pp. 707–725. doi: 10.1080/03057070.2014.943525.

Hoffman, M. T. and O'Connor, T. G. (1999) 'Vegetation change over 40 years in the Weenen/Muden area, KwaZulu-Natal: evidence from photo-panoramas', *African Journal of Range & Forage Science*, 16(924633133), pp. 71–88. doi: 10.2989/10220119909485721.

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'. doi: 10.1016/j.jaridenv.2008.07.004.

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. doi: 10.1007/s11258-006-9125-4.

Leakey, A. D. B. *et al.* (2009) 'Elevated CO 2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE', *Journal of Experimental Botany*, 60(10), pp. 2859–2876. doi: 10.1093/jxb/erp096.

Lück-vogel, M. and Strohbach, M. (2009) 'MONITORING OF SAVANNA DEGRADATION IN NAMIBIA USING LANDSAT TM / ETM + DATA Savanna Dynamics & Remote Sensing', (July).

Luvuno, L. *et al.* (2018) 'Woody Encroachment as a Social-Ecological Regime Shift', *Sustainability*. Multidisciplinary Digital Publishing Institute, 10(7), p. 2221. doi: 10.3390/su10072221.

Millennium Ecosystem Assessment (2005) *Ecosystems and human well-being: synthesis*. Washington, DC.

Mucina, L. and Rutherford, M. C. (2006) *The vegetation of South Africa, Lesotho and Swaziland*. South African National Biodiversity Institute.

Munyati, C., Shaker, P. and Phasha, M. G. (2011) 'Using remotely sensed imagery to monitor savanna rangeland deterioration through woody plant proliferation: a case study from communal and biodiversity conservation rangeland sites in Mokopane, South Africa', *Environmental Monitoring and Assessment*, 176(1–4), pp. 293–311. doi: 10.1007/s10661-010-1583-4.

Nackley, L. L. *et al.* (2018) 'CO2 enrichment does not entirely ameliorate Vachellia karroo drought inhibition: A missing mechanism explaining savanna bush encroachment', *Environmental and Experimental Botany*, 155, pp. 98–106. doi: 10.1016/j.envexpbot.2018.06.018.

O'Connor, T. G., Puttick, J. R. and Hoffman, M. T. (2014) 'Bush encroachment in southern Africa : changes and causes', *African Journal of Range and Forage Science*, 31(October), pp. 67–88. doi: 10.2989/10220119.2014.939996.

Polley, H. W. (1997) 'Implications of rising atmospheric carbon dioxide concentration for rangelands', *Journal of Range Management*, 50(6), pp. 562–577. doi: 10.2307/4003450.

Puttick, J. R., Hoffman, M. T. and Gambiza, J. (2011) 'Historical and recent land-use impacts on the vegetation of Bathurst, a municipal commonage in the Eastern Cape, South Africa', *African Journal of Range & Forage Science*, 28(March 2015), pp. 9–20. doi: 10.2989/10220119.2011.570946.

Ratajczak, Z., Nippert, J. B. and Ocheltree, T. W. (2014) 'Abrupt transition of mesic grassland to shrubland: evidence for thresholds, alternative attractors, and regime shifts', *Ecology*. Ecological Society of America, 95(9), p. 140221123657007. doi: 10.1890/13-1369.1.

Ratnam, J. *et al.* (2011) 'When is a "forest" a savanna, and why does it matter?', *Global Ecology and Biogeography*, 20(5), pp. 653–660. doi: 10.1111/j.1466-8238.2010.00634.x.

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*. Elsevier B.V., 416, pp. 276–288. doi: 10.1016/j.scitotenv.2011.10.067.

Russell, J. M. and Ward, D. (2014) 'Remote sensing provides a progressive record of vegetation change in northern KwaZulu-Natal, South Africa, from 1944 to 2005', *International Journal of Remote Sensing*, 35(3), pp. 904–926. doi: 10.1080/01431161.2013.873154.

Russell, J. and Ward, D. (2013) 'Vegetation change in northern KwaZulu-Natal since the Anglo-Zulu War of 1879: local or global drivers?', *African Journal of Range & Forage Science*, (November), pp. 1–17. doi: 10.2989/10220119.2013.827740.

Sankaran, M. *et al.* (2005) 'Determinants of woody cover in African savannas.', *Nature*, 438(7069), pp. 846–9. doi: 10.1038/nature04070.

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. doi: 10.1111/j.1466-8238.2007.00360.x.

Scholes, R. J. and Archer, S. R. (1997) 'Tree Grass Interactions in Savannas', *Annual Review of Ecology and Systematics*, pp. 517–544. doi: 0066-4162/97/1120-0517.

Shackleton, R. *et al.* (2013) 'Deagrarianisation and forest revegetation in a biodiversity hotspot on the Wild Coast, South Africa.', *PloS one*, 8(10), p. e76939. doi: 10.1371/journal.pone.0076939.

Skowno, A. L. *et al.* (2017) 'Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers', *Global Change Biology*, 23(6), pp. 2358–2369. doi: 10.1111/gcb.13529.

Staver, A. C. and Bond, W. J. (2014) 'Is there a "browse trap"? Dynamics of herbivore impacts on trees and grasses in an African savanna', *Journal of Ecology*. Edited by A. Austin, 102(3), pp. 595–602. doi: 10.1111/1365-2745.12230.

Stevens, N. *et al.* (2016) 'Woody encroachment over 70 years in South African savannahs: overgrazing, global change or extinction aftershock?', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1703), p. 20150437. doi: 10.1098/rstb.2015.0437.

Stevens, N. *et al.* (2017) 'Savanna woody encroachment is widespread across three continents', *Global Change Biology*, 23(1), pp. 235–244. doi: 10.1111/gcb.13409.

Symeonakis, E. and Higginbottom, T. (2014) ‘Bush encroachment monitoring using multi-temporal Landsat data and random forests’, *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. International Society for Photogrammetry and Remote Sensing, XL-2(2), pp. 29–35. doi: 10.5194/isprsarchives-XL-2-29-2014.

Vadigi, S. and Ward, D. (2014) ‘Herbivory effects on saplings are influenced by nutrients and grass competition in a humid South African savanna’, *Perspectives in Plant Ecology, Evolution and Systematics*, 16(1), pp. 11–20. doi: 10.1016/j.ppees.2013.10.002.

Venter, Z. S., Cramer, M. D. and Hawkins, H.-J. (2018) ‘Drivers of woody plant encroachment over Africa’, *Nature Communications*. Nature Publishing Group, 9(1), p. 2272. doi: 10.1038/s41467-018-04616-8.

Ward, D., Hoffman, M. T. and Collocott, S. J. (2014) ‘A century of woody plant encroachment in the dry Kimberley savanna of South Africa’, *African Journal of Range & Forage Science*, 31(1), pp. 1–15. doi: 10.2989/10220119.2014.914974.

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. doi: 10.1016/j.ppees.2005.10.001.

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. doi: 10.1111/j.1365-2028.2008.01051.x.

Wigley, B. J., Bond, W. J. and Hoffman, M. T. (2010) ‘Thicket expansion in a South African savanna under divergent land use: Local vs. global drivers?’, *Global Change Biology*, 16(3), pp. 964–976. doi: 10.1111/j.1365-2486.2009.02030.x.

CHAPTER 4: EARLY DETECTION OF WOODY ENCROACHMENT: A REGIME SHIFT ANALYSIS

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4.1 ABSTRACT

A number of early warning indicators for ecological transitions have been proposed that could help alert managers prior to a system undergoing a regime shift. However, empirical verification of these indicators has not kept up with the rapid growth in theoretical studies, as most indicators require long and detailed time series for quantification. We explore whether we are able to detect regime shifts and early warning indicators of these shifts in remote sensing data on woody encroachment in South Africa over the period 1990-2016. We used sequential t-tests analysis for regime shifts (STARS) to test for a shift, and autocorrelation (Moran's I) to test for early warning of the shift. STARS was able to detect a regime shift in our data in 2009, and as predicted, spatial autocorrelation increased leading up to the shift. This research suggests that there is potential to use remote sensing data to detect woody encroachment regime shifts. Spatial autocorrelation could serve as an indicator to monitor approaching thresholds. This information could inform management in support of ecosystem health and human well-being outcomes.

Keywords: *regime shifts; autocorrelation; early warning indicators; resilience, sequential t-tests analysis for regime shifts; savanna; South Africa*

4.2 Introduction

Regime shifts are large and persistent changes in the structure and function of social-ecological systems (Scheffer *et al.*, 2001). Regime shifts have been documented in a variety of different ecosystems, including lakes, coral reefs, savannas and forests (Scheffer *et al.*, 2001; Folke *et al.*, 2004). Regime shifts are widely regarded as undesirable as they often have considerable impacts on human well-being (Crépin *et al.*, 2012). For example, woody encroachment, the shift from a grassy savanna to a persistently woody savanna, threatens conservation and economic activity by suppressing the growth of grasses and reducing the amount of water in the landscape (Eldridge *et al.*, 2011; Anadón *et al.*, 2014; Gray and Bond 2013; Chapter 5). This results in a loss of productive grazing capacity of savannas for both cattle and wildlife.

An individual regime is characterised by a specific systemic structure, and is created and maintained by a specific set of feedback loops. All systems have competing balancing and reinforcing feedbacks loops that may function simultaneously. Whichever set of feedbacks dominate the system at a particular time will determine the system's present regime (Meadows, 2003). If a change occurs that weakens the dominance of the feedbacks maintaining a particular regime, the ecosystem state can be pushed beyond a threshold where the feedbacks of the alternate regime start dominating, and the system undergoes a regime shift (Chapter 2). These changes can occur abruptly through a shock in the system (such as a big flood) or gradually through a slow change of one of the system variables (Beisner, Haydon and Cuddington, 2003; Biggs *et al.*, 2012). The resilience of an ecosystem can be defined as its ability to absorb disturbances and still maintain the same structure, function and feedbacks – i.e., to sustain the same regime (Walker *et al.*, 2004).

Avoiding unintentional ecological regime shifts is widely regarded as desirable, but prediction of regime shifts is difficult (Biggs, Carpenter and Brock, 2009; Scheffer *et al.*, 2009; Crépin *et al.*, 2012). This is because the exact thresholds at which these shifts occur are seldom known (Carpenter, 2003; Scheffer *et al.*, 2009; Biggs *et al.*, 2012; Kéfi *et al.*, 2014). The thresholds at which regime shifts occur depend on the interaction between the drivers, system variables and feedbacks over time, which makes it difficult to anticipate critical thresholds because they vary over time and space (Carpenter, 2003; Scheffer *et al.*, 2009; Kéfi *et al.*, 2014). The risk of a particular regime shift in a particular place at a particular time is therefore often unknown (Carpenter, 2003; Crépin *et al.*, 2012).

Due to this uncertainty, recent theoretical work has focused on advancing generic early warning indicators of regime shifts (Scheffer *et al.*, 2009). These indicators are based on a phenomenon called 'critical slowing down' that generally occurs in a system prior to a regime shift (van Nes and Scheffer, 2007a). As a system moves closer to a threshold, the feedbacks that maintain a particular regime become weaker, and the system takes longer to recover from disturbance (van Nes and Scheffer, 2007b). Such indicators can therefore also be interpreted as indicators of changes in the resilience of a specific regime (Dai *et al.*, 2012; Dakos *et al.*, 2015; Scheffer *et al.*, 2015). These indicators focus on the changes in the dynamic behaviour of the system, specifically the variance and correlation patterns in time series data (Scheffer *et al.*, 2009). Both variance and correlation are expected to increase the closer a system is to a threshold (Dakos *et al.*, 2012). Similar patterns hold for spatial data (Scheffer *et al.*, 2009; Dakos *et al.*, 2012; Kéfi *et al.*, 2014). In modelled datasets, spatial autocorrelation increases prior to a shift and then drops after the transition (Dakos *et al.*, 2010). Rising spatial autocorrelation has therefore been found to be a robust indicator of critical slowing down (Dakos *et al.*, 2010, 2012).

Where a large change has occurred in an ecosystem, determining whether it represents a regime shift is often difficult (Crépin *et al.*, 2012). A number of statistical tests and methods have also been used to detect regime shifts in time series data (Easterling and Peterson, 1995; Rodionov, 2004). Among these tests, sequential t-tests are the most commonly used. Rodionov (2004) developed the STARS (sequential t-test analysis of regime shifts) method which has been successfully used to detect regime shifts in time series data (Rodionov and Overland, 2005; Howard *et al.*, 2007; Marty, 2008). A shortcoming of these tests is that while they can reveal whether a shift has occurred or not, they do not give insight into what the drivers or feedbacks of the shift are.

In this paper we test whether woody encroachment in a South African savanna system represents a regime shift. Our analysis is based on a 26-year Landsat-derived dataset on changes in tree-cover in the Hlabisa area of South Africa (Chapter 3). Woody encroachment is prevalent across the world's savannas and has been a problem in southern Africa for nearly a century (Stevens *et al.*, 2016; Stevens, Lehmann, *et al.*, 2017). Current research shows that the rate of encroachment is increasing (Chapter 3; Buitenwerf *et al.*, 2012). While there have been many studies of bush encroachment, and the drivers and impacts of this process are reasonably well-understood, very few studies have specifically tested whether the changes in tree cover constitutes a regime shift, and whether early warning of these shifts can be detected. Such information would be highly relevant to managers of savanna landscapes.

4.3 METHODS

4.3.1 Study Area

The Hlabisa district of KwaZulu-Natal, South Africa (28.00°S to 28.25°S and 32.00°E to 32.58°E) has undergone substantial woody encroachment in recent decades (Wigley, Bond and Hoffman, 2009; Chapter 3). Land use in the study area comprises of communal lands (33%) and a state conservation area (38%). Communal lands are primarily used for small-scale subsistence farming, and are under traditional tenure arrangements. The 96000 ha state conservation area; Hluhluwe-Imfolozi Park was established in 1895 and is managed by Ezemvelo KZNWildlife - a parastatal conservation authority.

The mean annual precipitation (MAP) of the area ranges from 700 mm - 990 mm per annum, with most of the rainfall falling in the summer months of September to March. South African savannas falling into this rainfall range have experienced the highest rate of woody encroachment (Skowno *et al.*, 2017). Temperatures in the area are warm to hot, particularly during the summer months. Mean annual temperature in the region is 22.5 °C with a mean minimum July temperature of 13 °C and a mean maximum February temperature of 35 °C (Wigley, Bond and Hoffman, 2009).

4.3.2 Data analysis

Time series data were derived from land cover classification of Landsat imagery of Hlabisa, South Africa (Chapter 3). The images were chosen on the basis of season and high rainfall events to ensure that the observed changes were not phenology-driven. We used satellite imagery taken at the end of the rainy season and a few weeks after at least 200 mm of rainfall. Eleven images (covering 1990-2016) of the appropriate timing that were cloud free were used as the basis for the analysis. Urban areas and commercial agricultural areas were excluded from the analysis. For each of the 11 images, we calculated the percentage of the entire image that was classified as covered by trees, to obtain a time series that spans 26 years.

To test if the observed differences in tree cover constitute a regime shift, we applied the STARS method to the tree data (Rodionov, 2004). The method uses a sequential approach to determine the timing of a regime shift within time series data. This method differs from other methods of detecting regime shifts in that it requires a minimum of ten data points (years) and prevents the deterioration of the test statistic towards the end of the time-series (Rodionov, 2004), making it possible to detect a shift near the end of a time series. For each new observation in a time series, a test is performed to see if it differs significantly from the mean of the current regime, and if it is found to be greater or less than the critical level of the current regime mean, then the current time (year) is marked as a possible change point. The algorithm can pick up regime shifts resulting from both abrupt and gradual changes in the time series.

The identification of a regime shift using the STARS method is based on calculating a regime shift index (RSI), which represents a cumulative sum of normalized deviations of the time-series values from the hypothetical mean level for the new regime (Rodionov and Overland, 2005).

$$\mathrm{RSI}_c = \sum_{i=c}^{c+m} \left(\frac{x_i}{l\sigma_l}\right), m = 0, \ldots, l-1$$

Where c is the year of the possible start of a new regime, l is the length of regime to be determined, x_i is the new value in the time series, σ_l is the average variance for a running l-year intervals in the time series.

To test if we can detect an indication of ‘critical slowing down’ in our study area we ran a spatial autocorrelation test for each of the 11 years. We used ArcGIS 10.3 (Esri, California, USA) to convert the land cover images into polygons, and ran a model which measures spatial autocorrelation based on feature locations and attribute values using the Global Moran's I statistic. We plotted the resulting Moran’s index values to visually inspect patterns in spatial autocorrelation over time.

4.4 Results

STARS detected a regime shift in the overall study area in 2009 (Table 4.1). The average tree-cover (22 %) in the period 2009-2016 is significantly different to that of the period 1990-2006 (36%) ($p < 0.001$; $t = -12.955$). Looking at the different land use areas, a regime shift was detected in the conservation area also in 2009, and in the community area in 2011.

We used the results from Moran's I index to investigate if the system showed signs of critical slowing down before the regime shift in 2009. We found that the spatial autocorrelation increased over time, with an apex in 2006 and then decreased from 2009 onwards (Figure 4.1). The increasing auto-correlation suggests the ecosystem was losing resilience and confirms that a regime shift occurred in the Hlabisa area in the late 2000s.

Table 4.1: **Regime shift Index values of tree cover.** No significant results were detected prior to 2009 so we reduced the table by omitting years 1990-2005. All the non-zero values indicate years when a shift was detected. The first column gives results for the Hlabisa area overall, and the other two columns for communal and conservation areas respectively.

Year	Hlabisa	Community	Conservation
2006	0	0	0
2009	1.042781	0	0.798823822
2011	0	1.389299238	0
2016	0	0	0

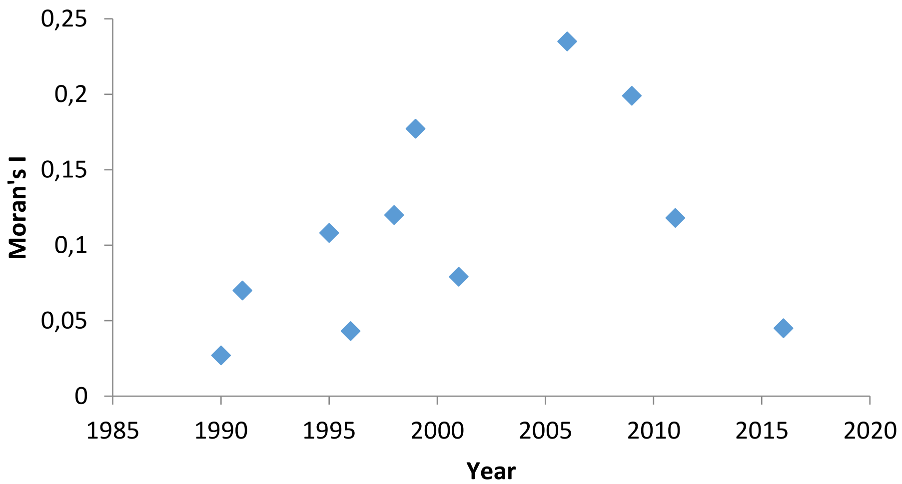

Figure 4.1: Spatial Autocorrelation (Global Moran's I) statistic across the study area.

4.5 Discussion

Although it has been established that the dynamics underlying woody encroachment can lead to a regime shift (Scheffer *et al.*, 2001; Ratajczak, Nippert and Ocheltree, 2014; Luvuno *et al.*, 2018), this study represents one of the very few studies that empirically tests whether observed increases in woody cover represent a regime shift (D'Odorico, Okin and Bestelmeyer, 2012; Ratajczak, Nippert and Ocheltree, 2014).

The results from the STARS analysis indicates that a regime shift occurred in Hlabisa overall as well as in the conservation area in 2009, and in 2011 in the communal areas. This suggests that tree cover in Hlabisa has passed a threshold where the woody regime is now sustained by self-reinforcing feedbacks (Luvuno *et al.*, 2018; Chapter 2). An interaction of droughts in the early 2000s and the subsequent reduction in fire frequency and intensity, along with increased atmospheric carbon dioxide concentrations likely contributed to the regime shift (Chapter 3). The slightly delayed shift in the communal area is likely due to tree harvesting which has reduced substantially since electrification of the area (Chapter 5). According to Stats SA (2018), 29% of the households in the area had electricity in 2001 which increased to 93% by 2011.

The estimated regime shift in 2009 is confirmed by the results from Moran's index. Spatial auto-correlation evaluates the patterns in the landscape. The results of the Moran's I suggests our study site was initially very heterogeneous, and as tree cover increased in the landscape, the patterns in the landscape became more clustered (Puttick, Hoffman and Gambiza, 2011; Komac *et al.*, 2013). After 2006, tree and grass cover are almost the same percentage in the landscape (Chapter 3) and demonstrate a more dispersed pattern. This study represents an empirical validation of using spatial auto-correlation to detect the loss of resilience prior to a regime shift, with a short and patchy time series.

STARS has been successfully used to detect climate-related regime shifts (Rodionov and Overland, 2005; Howard *et al.*, 2007; Marty, 2008), but this is the first application of the method to woody encroachment. The ability of the method to detect regime shifts at the end of the time series is very useful, and enabled us to detect a regime shift late in our time series. STARS could be a very useful monitoring tool as it allows one to analyse time series data as it is generated. Most other regime shift detection methods require long and detailed time series data (Rodionov and Overland, 2005; Howard *et al.*, 2007) and are therefore less nimble in their application. Compared to other methods, STARS presents much more potential for application in practical management settings where adaptive management decisions often need to be rapid and decisive.

Similarly, this study provides an empirical demonstration of the use of spatial autocorrelation to monitor and detect regime shifts. We were able to detect changes in auto-correlation despite a patchy time series. This is particularly promising as spatial data are becoming increasingly accessible.

Knowing that a regime shift has occurred (STARS), or that a system is approaching a critical threshold (spatial autocorrelation), provides managers with information that can inform actions to prevent undesirable shifts, encourage desirable shifts (as in restoration contexts), or prepare for shifts that cannot be avoided. Regime shifts can have large impacts on social, ecological and economic systems, and reversing a shift may require expensive interventions and in some cases may be impossible. This study presents one of a limited number of empirical examples of the practical application of methods to detect regime shifts and provide potential early warning to avoid regime shifts.

4.6 CONCLUSION

This study indicates that the woody encroachment occurring in Hlabisa constitutes a regime shift. The results of this study demonstrate the first application of STARS to detect woody encroachment and an empirical application of spatial autocorrelation to assess loss of resilience leading up to a regime shift. Given the increasing availability of remote sensing data, these results suggest that STARS and spatial autocorrelation could be used in practical management settings to monitor, assess and manage woody encroachment. Once managers know a potential regime shift is approaching or has occurred, a broader systems analysis is needed to identify which drivers and feedbacks have changed and therefore need weakening or strengthening to manage the system for desired outcomes. Overall, it is important to understand the mechanisms the drive woody encroachment and likewise not rely solely on the generic indicators, especially as we try to understand why indicators work or do not work.

4.7 REFERENCES

Anadón, J. D. *et al.* (2014) 'Effect of woody-plant encroachment on livestock production in North and South America.', *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences, 111(35), pp. 12948–53. doi: 10.1073/pnas.1320585111.

Beisner, B., Haydon, D. and Cuddington, K. (2003) 'Alternative stable states in ecology', *Frontiers in Ecology and the Environment*. Wiley-Blackwell, 1(7), pp. 376–382. doi: 10.1890/1540-9295(2003)001[0376:ASSIE]2.0.CO;2.

Biggs, R. *et al.* (2012) 'Regime Shifts', in Hastings, A; Gross, L. (ed.) *Encyclopedia of Theoretical Ecology*. Ewing, NJ, USA: University of California Press, pp. 609–617.

Biggs, R., Carpenter, S. R. and Brock, W. A. (2009) 'Turning back from the brink: Detecting an impending regime shift in time to avert it', *Proceedings of the National Academy of Sciences*, 106(3), pp. 826–831. doi: 10.1073/pnas.0811729106.

Buitenwerf, R. *et al.* (2012) 'Increased tree densities in South African savannas: >50 years of data suggests CO2 as a driver', *Global Change Biology*, 18(2), pp. 675–684. doi: 10.1111/j.1365-2486.2011.02561.x.

Carpenter, S. (2003) *Regime Shifts in Lake Ecosystems:Pattern and Variation: 15 Excellence in Ecology: Amazon.co.uk: Stephen R Carpenter, Otto Kinne: Books*. Edited by O. Kinne. Oldendorf: International Ecology Institute. Available at: https://www.amazon.co.uk/Regime-Shifts-Lake-Ecosystems-Excellence/dp/3946729150 (Accessed: 5 November 2018).

Crépin, A.-S. *et al.* (2012) 'Regime shifts and management', *Ecological Economics*, 84, pp. 15–22. doi: 10.1016/j.ecolecon.2012.09.003.

D'Odorico, P., Okin, G. S. and Bestelmeyer, B. T. (2012) 'A synthetic review of feedbacks and drivers of shrub encroachment in arid grasslands', *Ecohydrology*, 5(October 2011), pp. 520–530. doi: 10.1002/eco.259.

Dai, L. *et al.* (2012) 'Generic Indicators for Loss of Resilience Before a Tipping Point Leading to Population Collapse', *Science*, 336(6085), pp. 1175–1177. doi: 10.1126/science.1219805.

Dakos, V. *et al.* (2010) 'Spatial correlation as leading indicator of catastrophic shifts', *Theoretical Ecology*, 3(3), pp. 163–174. doi: 10.1007/s12080-009-0060-6.

Dakos, V. *et al.* (2012) 'of critical slowing down R eports', *Ecology*, 93(2), pp. 264–271.

Dakos, V. *et al.* (2015) 'Resilience indicators: Prospects and limitations for early warnings of regime shifts', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 370(1659), pp. 1–10. doi: 10.1098/rstb.2013.0263.

Easterling, D. R. and Peterson, T. C. (1995) 'A new method for detecting undocumented discontinuities in climatological time series', *International Journal of Climatology*. Wiley-Blackwell, 15(4), pp. 369–377. doi: 10.1002/joc.3370150403.

Eldridge, D. J. *et al.* (2011) 'Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis.', *Ecology letters*, 14(7), pp. 709–22. doi: 10.1111/j.1461-0248.2011.01630.x.

Folke, C. *et al.* (2004) 'Regime Shifts, Resilience, and Biodiversity in Ecosystem Management', *Annual Review of Ecology, Evolution, and Systematics*, 35(1), pp. 557–581. doi:

10.1146/annurev.ecolsys.35.021103.105711.

Gray, E. F. and Bond, W. J. (2013) ‘Will woody plant encroachment impact the visitor experience and economy of conservation areas?’, *Koedoe*, 55(1), pp. 1–9. doi: 10.4102/koedoe.v55i1.1106.

Howard, J. A. E. *et al.* (2007) ‘Application of the sequential t-test algorithm for analysing regime shifts to the southern Benguela ecosystem’, *African Journal of Marine Science*, 29(3), pp. 437–451. doi: 10.2989/AJMS.2007.29.3.11.341.

Kéfi, S. *et al.* (2014) ‘Early warning signals of ecological transitions: Methods for spatial patterns’, *PLoS ONE*, 9(3), pp. 10–13. doi: 10.1371/journal.pone.0092097.

Komac, B. *et al.* (2013) ‘Modeling shrub encroachment in subalpine grasslands under different environmental and management scenarios.’, *Journal of environmental management*, 121, pp. 160–9. doi: 10.1016/j.jenvman.2013.01.038.

Luvuno, L. *et al.* (2018) ‘Woody Encroachment as a Social-Ecological Regime Shift’, *Sustainability*. Multidisciplinary Digital Publishing Institute, 10(7), p. 2221. doi: 10.3390/su10072221.

Marty, C. (2008) ‘Regime shift of snow days in Switzerland’, *Geophysical Research Letters*, 35(12), pp. 1–5. doi: 10.1029/2008GL033998.

Meadows, D. (2003) *Thinking in Systems: A Primer*. London: Chelsea Green Publishing. Available at: https://books.google.co.za/books/about/Thinking_in_Systems.html?id=JSgOSP1qklUC&pgis=1 (Accessed: 1 February 2016).

van Nes, E. H. and Scheffer, M. (2007a) ‘Slow Recovery from Perturbations as a Generic Indicator of a Nearby Catastrophic Shift’, *The American Naturalist*, 169(6), pp. 738–747. doi: 10.1086/516845.

van Nes, E. H. and Scheffer, M. (2007b) ‘Slow Recovery from Perturbations as a Generic Indicator of a Nearby Catastrophic Shift’, *The American Naturalist*, 169(6), pp. 738–747. doi: 10.1086/516845.

Puttick, J. R., Hoffman, M. T. and Gambiza, J. (2011) ‘Historical and recent land-use impacts on the vegetation of Bathurst, a municipal commonage in the Eastern Cape, South Africa’, *African Journal of Range & Forage Science*, 28 (March 2015), pp. 9–20. doi: 10.2989/10220119.2011.570946.

Ratajczak, Z., Nippert, J. B. and Ocheltree, T. W. (2014) ‘Abrupt transition of mesic grassland to shrubland: evidence for thresholds, alternative attractors, and regime shifts’, *Ecology*. Ecological Society of America, 95(9), p. 140221123657007. doi: 10.1890/13-1369.1.

Rodionov, S. N. (2004) ‘A sequential algorithm for testing climate regime shifts’, *Geophysical Research Letters*, 31(9), pp. 2–5. doi: 10.1029/2004GL019448.

Rodionov, S. and Overland, J. E. (2005) ‘Application of a sequential regime shift detection method to the Bering Sea ecosystem’, *ICES Journal of Marine Science*, 62(3), pp. 328–332. doi: 10.1016/j.icesjms.2005.01.013.

Scheffer, M. *et al.* (2001) ‘Catastrophic shifts in ecosystems.’, *Nature*, 413(6856), pp. 591–596. doi: 10.1038/35098000.

Scheffer, M. *et al.* (2009) ‘Early-warning signals for critical transitions.’, *Nature*. Nature Publishing Group, 461(7260), pp. 53–9. doi: 10.1038/nature08227.

Scheffer, M. *et al.* (2015) ‘Generic Indicators of Ecological Resilience: Inferring the Chance of a Critical Transition’, *Annual Review of Ecology, Evolution, and Systematics*, 46(1), pp. 145–167. doi: 10.1146/annurev-ecolsys-112414-054242.

Skowno, A. L. *et al.* (2017) ‘Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers’, *Global Change Biology*, 23(6), pp. 2358–2369. doi: 10.1111/gcb.13529.

StatsSA (2018) *Statistics by place.* Statistics South Africa, Pretoria.

Stevens, N. *et al.* (2016) ‘Woody encroachment over 70 years in South African savannahs: overgrazing, global change or extinction aftershock?’, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1703), p. 20150437. doi: 10.1098/rstb.2015.0437.

Stevens, N. *et al.* (2017) ‘Savanna woody encroachment is widespread across three continents’, *Global Change Biology*, 23(1), pp. 235–244. doi: 10.1111/gcb.13409.

Walker, B. *et al.* (2004) ‘Resilience, Adaptability and Transformability in Social – ecological Systems’, *Ecology and Society*, 9(2), p. 5. doi: 10.1103/PhysRevLett.95.258101.

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. doi: 10.1111/j.1365-2028.2008.01051.x.

CHAPTER 5: PERCEIVED IMPACTS OF WOODY ENCROACHMENT ON ECOSYSTEM SERVICES IN HLUHLUWE, SOUTH AFRICA

This chapter is intended for submission in Ecosystems: Luvuno, LB; Biggs, R; Stevens, N; Esler, K. Perceived impacts of woody encroachment on ecosystem services in Hluhluwe, South Africa

5.1 ABSTRACT

Woody encroachment is reported to have negative impacts on ecosystem services, with direct impacts on the people living in the affected areas. However, very few studies focus on the impacts of woody encroachment on local land users and their livelihoods, and how this in turn influences their ecosystem management strategies. In this study we determine how different land users (rural communities and game reserve managers) perceive woody encroachment, how woody encroachment affects ecosystem services and what are the costs of reversing woody encroachment for the different land users? Semi-structured questionnaires were used to interview the different land users. The majority of interviewees perceived trees to be increasing in the landscape (83%). The majority of community members thought woody encroachment was harmful to their household, general well-being. Private game reserve managers mostly perceived woody encroachment to be both harmful and beneficial, while the majority of state reserve managers perceived woody encroachment to be beneficial or had no impact to their business. Reduced grazing capacity was the highest cited ecosystem impact, along with the increased fear of criminals and wild animals, reduced water in the landscape, and the high costs of tree clearing. Community members cited the reduced usage of trees as the reason for woody encroachment, compared to reserve managers who mostly cited increased CO_2 and the impacts of global warming. Only 26% of the respondents in the community areas cleared trees on their properties, with an average of R367/yr spent on clearing, compared to R293 751 and R163000 spent in private game reserves and government reserves respectively.

Keywords: *Woody encroachment; ecosystem services; savanna; South Africa*

5.2 Introduction

One of the five grand challenges for earth system and sustainability research is to determine how to anticipate, avoid, and manage disruptive global environmental change such as regime shifts (Reid *et al.*, 2010). Regime shifts are large and persistent changes in structure and function of ecosystems and social-ecological systems (SES) (Scheffer *et al.*, 2001). One globally important regime shift is woody encroachment in savannas, which is the shift from open grassy savanna to a persistently woody savanna (Daskin, Stalmans and Pringle, 2016; Stevens, Lehmann, *et al.*, 2017). Woody encroachment can potentially affect large parts of the planet, as savannas occupy 20% of the earth's land surface and one fifth of humanity relies on the ecosystem services they provide (Sankaran *et al.*, 2005; Lehmann *et al.*, 2014).

Regime shifts can alter the ecosystem services provided by an ecosystem, as sets of species with particular traits (e.g. grasses) are replaced by species with fundamentally different traits (e.g. trees) which functionally provide different services (Loreau *et al.*, 2001; Diaz *et al.*, 2004; Cardinale *et al.*, 2012). Tree dominated ecosystems, for example, provide services such as raw tree materials for heating and building, whereas open grass dominated ecosystems provide livestock, crop production and water regulation services (Lawes, Macfarlane and Eeley, 2004). Regime shifts therefore lead to a reduction in some ecosystem services, although there may also be gains in other services (Grossman, 2015; King, Cavender-Bares, Balvanera, Mwampamba and Polasky, 2015; Troell *et al.*, 2005; Ye *et al.*, 2018). These changes affect human well-being by impacting the necessary materials for a good life, security, health, and social and cultural relations (Millennium Ecosystem Assessment, 2005).

Woody encroachment is known to negatively impact biodiversity, tourism, ecohydrology, grazing, agriculture, and land use (Briggs *et al.*, 2005; Huxman *et al.*, 2005; Eldridge *et al.*, 2011; Archer and Predick, 2014; Honda *et al.*, 2016). As a result of these impacts, much effort has been invested to understand the drivers of woody encroachment (Moustakas *et al.*, 2010; Wigley, Bond and Hoffman, 2010; O'Connor, Puttick and Hoffman, 2014; Stevens *et al.*, 2016) and the associated impacts, especially on biodiversity and grazing capacity. However, few studies have investigated the impacts of woody encroachment on local land users and their livelihoods (Mugasi, Sabiiti and Tayebwa, 2000; Wigley, Bond and Hoffman, 2009; Shackleton *et al.*, 2013), and how this in turn influences their ecosystem management strategies. The studies above either looked at a single impact of woody encroachment, and the perceptions of the drivers where some impacts were captured. The need for a deeper understanding of how land users perceive and rely on ecosystem services has been identified as a critical research priority (Carpenter *et al.*, 2009). This is particularly important for the rural poor in developing countries who often rely disproportionally on nature for their sustenance and livelihoods (McNally *et al.*, 2016).

The perspectives and needs of poor land users is especially important because their dependence on ecosystem services may foster priorities that are different to, for instance, tourism and conservation organizations (McNally *et al.*, 2016). Different land users are likely to respond differently to changes in ecosystem services (Carpenter *et al.*, 2009). This diversity can be seen at multiple scales (e.g., household, village, and region) and responses at one scale may act synergistically with or contrary to the effects of diverse responses at another scale (Leslie and McCabe, 2013). For this reason, it is important to quantify the trade-offs and synergies among ecosystem services and how they affect different users, as well as their implications for local policies and management interventions. In many cases, interventions are implemented, and often fail, because they are implemented without consulting land users about their perceptions and needs (Menzel and Teng, 2009; McNally *et al.*, 2016).

This paper investigates the impacts of woody encroachment on ecosystem services and different land users in the Hluhluwe area of South Africa. Hluhluwe lies within the savanna region, which is the dominant biome in South Africa and home to over 11 million people (Twine *et al.*, 2003). Savannas have the highest number of direct ecosystem service users in South Africa (Hamann, Biggs and Reyers, 2015). Twenty percent of the country's households are involved in agriculture (StatsSA, 2018), many of them based in savannas, where the main land uses are subsistence and commercial livestock farming, and national and local nature reserves (Higgins, Shackleton and Robinson, 1999). Livestock farming is the country's biggest agricultural sector and contributes substantially to food security in the country. It is also well documented that rural communities in South Africa supplement their livelihoods with natural resources, specifically wood for fuel and building materials, grass for thatching and brooms, and plant products for medicinal purposes (Lawes, Macfarlane and Eeley, 2004; Thondhlana, Vedeld and Shackleton, 2012; Hamann, Biggs and Reyers, 2015). Furthermore, South African savannas are important conservation areas and support significant numbers of the world's remaining megafauna. These nature reserves are also important tourist attractions and sources of revenue (Higgins, Shackleton and Robinson, 1999; Gray and Bond, 2013). Woody encroachment negatively affects game viewing which impacts visitor numbers in reserves

(Gray and Bond, 2013). Continued encroachment of savannas by woody plants is therefore expected to have substantial negative impacts on both commercial and subsistence farming, as well as tourism in South Africa. This emphasises the need to better understand how woody encroachment and people's perceptions of these changes affect the livelihoods of the users.

Hluhluwe is one of the areas in South Africa that has recently undergone woody encroachment and the landscape comprises of different land users, providing a good area for investigation of the effects of woody encroachment. The study spans a state owned conservation area, communal areas that comprise mainly of small-scale subsistence farming, and private game reserves. The key questions addressed by the study include:

(1) How do different land users perceive woody encroachment?

(2) How does woody encroachment affect ecosystem services valued by different users, and

(3) What are the costs of reversing woody encroachment for different land users?

5.3 METHODS

5.3.1 Study Area

Hluhluwe lies in the Hlabisa district of KwaZulu-Natal, South Africa (28.00°S to 28.25°S and 32.00°E to 32.58°E) (Figure 5.1). This area has undergone substantial woody encroachment in the last 70 years (Wigley, Bond and Hoffman, 2009), and was selected through a literature search and by consulting ecologists and researchers in the region.

Hlabisa is largely inhabited by black Africans who make up 99.4% of the total population, with 94% of the people speaking IsiZulu as a home language. Poverty is a major issue, as reflected by the high unemployment rate of 52.6%, rising to 61.9% unemployment amongst the youth (StatsSA 2018). The level of education for the community of Hlabisa is relatively low: 22% of the population have no schooling, 26% have completed high school, and just 1.7% have higher education qualifications (StatsSA 2018).

The mean annual precipitation (MAP) of the area ranges from 700 mm - 990 mm per annum, with most of the rainfall falling in the summer months of September to March. South African savannas falling into this rainfall range have experienced the highest rate of woody encroachment (Skowno *et al.*, 2017). Temperatures in the area are warm to hot, particularly during the summer months. Mean annual temperature in the region is 22.5 °C with a mean minimum July temperature of 13 °C and a mean maximum February temperature of 35 °C (Wigley, Bond and Hoffman, 2009).

Land use in the area comprises communal lands, national conservation areas and private farms and game reserves. Communal lands are areas that have been utilized communally by rural communities since the inception of the Zulu Kingdom in 1816. (Higgins, Shackleton and Robinson, 1999). Under the Apartheid regime, this area operated under traditional tenure arrangements, and this is still the case today. Commercial farming in this area started in the early 1900s with cattle farming being the predominant land-use practice. From the 1970s, many of the commercial farmers in the area changed from cattle farming to game farming (Wigley, Bond and Hoffman, 2009). Many of the commercial farms now form conglomerates of private game reserves that are relatively newly established with the objective of conserving local biodiversity, often for commercial gain through tourism activities (Higgins, Shackleton and Robinson, 1999). The state owned conservation area, Hluhluwe iMfolozi Game Reserve, aims to ensure conservation and the sustainable use of the biodiversity under its jurisdiction.

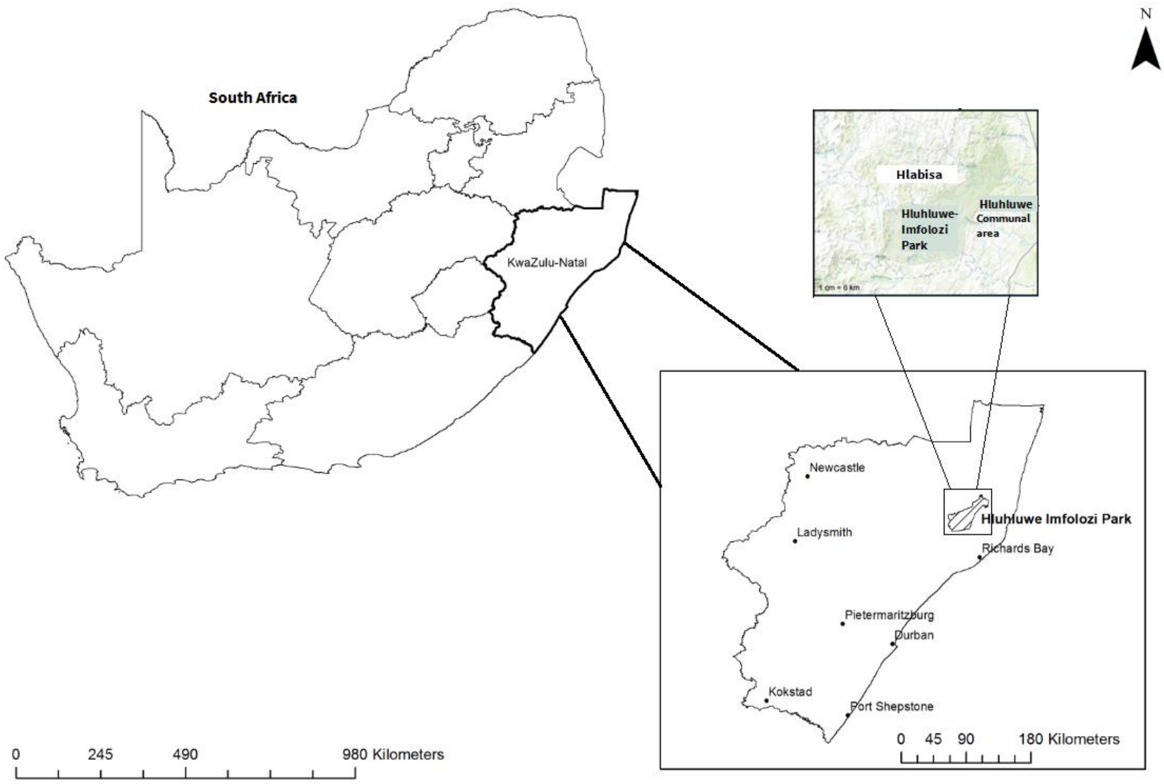

Figure 5.1: Study site location: the Hlabisa district in Zululand.

5.3.2 Data collection

Community members living in the communal lands, as well as conservation managers on the private and state-owned game reserves were interviewed. The interviews sought to gain insight into their perceptions of what changes had occurred in the landscape, what these changes mean to them, how it has impacted their lives, and the cost of managing woody encroachment. The interviews were also used to determine what the different land users are doing to counteract the changes.

Interviews were undertaken using semi-structured questionnaires (Appendix 1). In the communal areas, household interviews were conducted with thirty community members from four villages. Only people who have been living in the area for over 20 years were interviewed. This was mainly to exclude minors from the study and because woody encroachment in the area occurred 10-20 years prior to the inception of the study. The interviewees were a mixture of ages, men and women, and different levels of education and occupations (Table 5.1). Fewer people were interviewed in the conservation areas, given the limited total number of managers of these areas. In the private game reserves, 4 reserve managers were interviewed, who collectively manage over 70 000 ha. In the state run Hluhluwe iMfolozi Game Reserve, we conducted 6 interviews with the park manager and section rangers. The interviews were conducted in Zulu or English depending on the interviewees' preferred language of communication. Participation was on a voluntary, confidential basis, and the research was approved by the Stellenbosch University Research Ethics Committee.

The interviews were conducted between February and March 2018 and were on average 45 minutes long. The interviews included a combination of closed and open ended questions, which allowed us to quantitatively assess certain aspects of change, while at the same time allowing the interviewees' perceptions and qualitative data to emerge without being pre-empted. The open ended questions included questions related to the perceived causes, impacts, costs, and the management of woody encroachment. The costs of encroachment were derived directly from a question asking about the total cost of woody encroachment management over the past year. The interviewer filled out the questionnaire during the interview, which was also digitally recorded.

Table 5.1: Demographics of the sample population of the different land users interviewed.

Land Users	Gender	Mean Age (years)	Ethnicity	Mean Education
Community Members *(n) = 30*	63% F	53.6 ± 12.5	100% Black	60% Grade 10 or less
State Reserve Managers *(n) = 6*	100% M	41.7 ±1.1	83% Black	67% post graduate
Private Reserve Managers *(n) = 4*	50% F	38 ± 3.8	100% White	100% post graduate

5.3.3 Data analysis

Data from the interviews were tabulated for data analysis. Fisher exact tests were employed to examine whether the perceived problems differed across the different land users. The Fisher Exact test is a test of significance that is used in the place of chi square when the sample size is small.

5.4 Results

5.4.1 Perceptions of woody encroachment

There were no significant differences in perception of the amount of woody encroachment between the different land users (Figure 5.2). The majority of interviewees thought the number of trees in the landscape was increasing (83%). All the game reserve managers, on both the private and state run reserves, reported that woody encroachment is occurring in their reserves. Fifty percent of the community members said trees were increasing on their property, and 83% said trees were spreading in the area. Only 20% of the interviewed community members reported trees to have either decreased or remained constant.

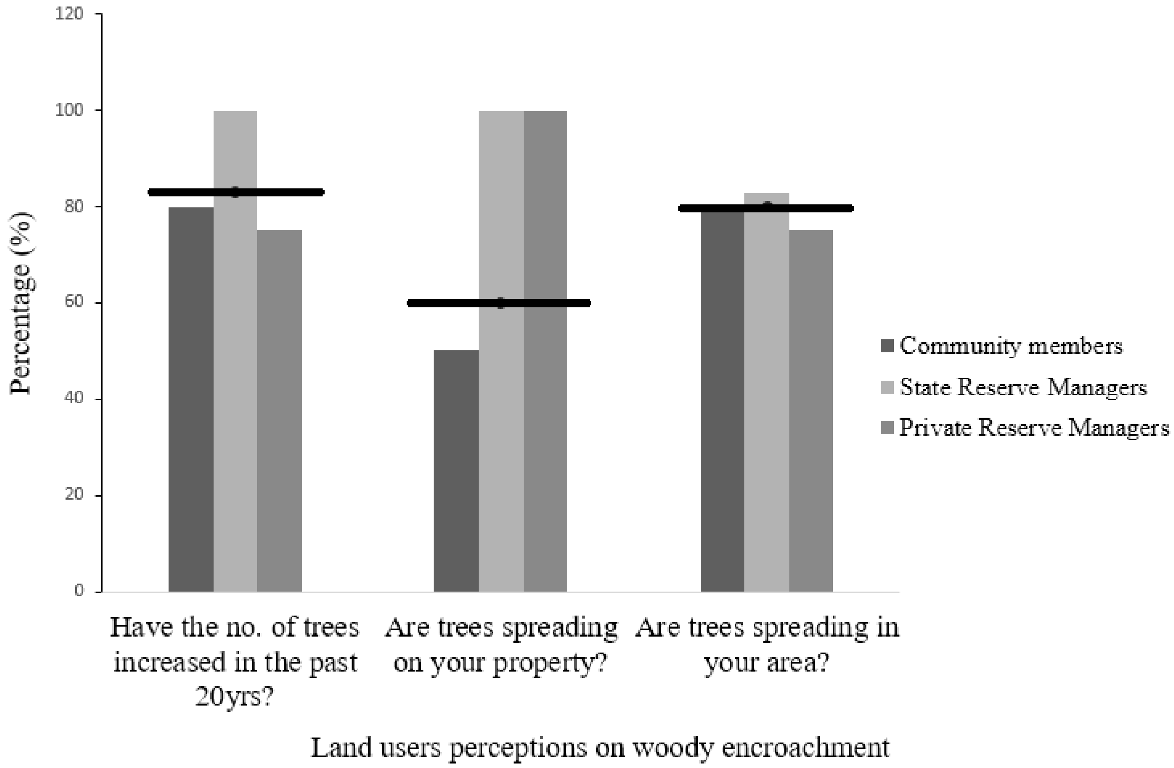

Figure 5.2: Stakeholder responses regarding their perceptions of woody encroachment. *Black lines are the average across the land users.*

A list of perceived causes of encroachment was compiled based on the open-ended responses to the questionnaire (Table 5.2). Most people (58%) cited the reduced usage of trees as the reason for woody encroachment in the area. The community members thought reduced use (38%) and deagrarianisation (46%) were the main causes of woody encroachment. Some community members thought encroachment was part of the natural process of pollination and germination related to rainfall (17%). The reserve managers thought increased carbon dioxide, increased variability in droughts and floods, mismanagement of fire, and the historical legacy of the landscape were the main causes. Other causes mentioned were low game numbers, fragmentation of landscapes, overgrazing and a lack of managerial expertise.

Table 5.2: Land user perceptions of the causes of woody encroachment. *(X^2 = 72.15; df = 24; $p < 0.01$). Dash (-) refers to 0% reported cause.*

Causes of woody encroachment	Community members	State Reserve Managers	Private Reserve Managers	Mean
Reduced tree use	38%	17%	-	30.6%
Deagrarianisation	46%	-	-	33.7%
Natural process	17%	17%	-	15.3%
Increased carbon dioxide	-	67%	50%	18.4%
Increased variability in droughts and floods	-	67%	50%	18.%
Mismanagement of fire	-	33%	50%	12.2%
Historical legacy	-	-	50%	6.1%
Don't know	8%	-	25%	9.2%
Low game numbers	8%	17%	-	9.2%
Fragmentation of landscapes	-	-	25%	3.1%
Overgrazing	-	-	25%	3.1%
Lack of managerial expertise	-	-	25%	3.1%

5.4.2 Effects on ecosystem services

There were no significant differences in how land users perceived the impact of woody encroachment on ecosystem services. Fifty four percentage of community members thought woody encroachment was harmful to their household and general well-being (Figure 5.2). This was mainly through the reduction of grass for grazing and increased fear of attacks by wild animals such as leopard and hyena (Table 5.3). Other notable impacts of woody encroachment mentioned were the reduction of water supply, increased fear of criminals who hide in the thick bushes, livestock getting lost in the bushes, and having to walk further because the bushes close walking paths. A few community members thought woody encroachment was both beneficial and harmful (17%) or just beneficial (17%). The most reported benefit was firewood, even though 93% of the respondents reported a decreased use of trees over time. When asked how much firewood people collected, only 2 households reported that they still relied on firewood with no change in use over the years. On average, 21 hrs/yr are spent collecting firewood.

Woody encroachment was perceived to be beneficial by 50% of the state game reserve managers, whereas 50% of the private game reserve managers thought woody encroachment was both harmful and beneficial (Figure 5.3). State reserve managers reported the reduction of grass for grazing by game animals and the increased fear of wild animal attacks during patrols (33%) as the main negative impacts of woody encroachment. In private game reserves, the impacts of woody encroachment were mainly the high cost of clearing (75%), complaints from the guests not being able to see the game, and the loss of grazing potential (50%). All the game reserve managers noted the beneficial impact of increased food for browsers and having a heterogeneous landscape.

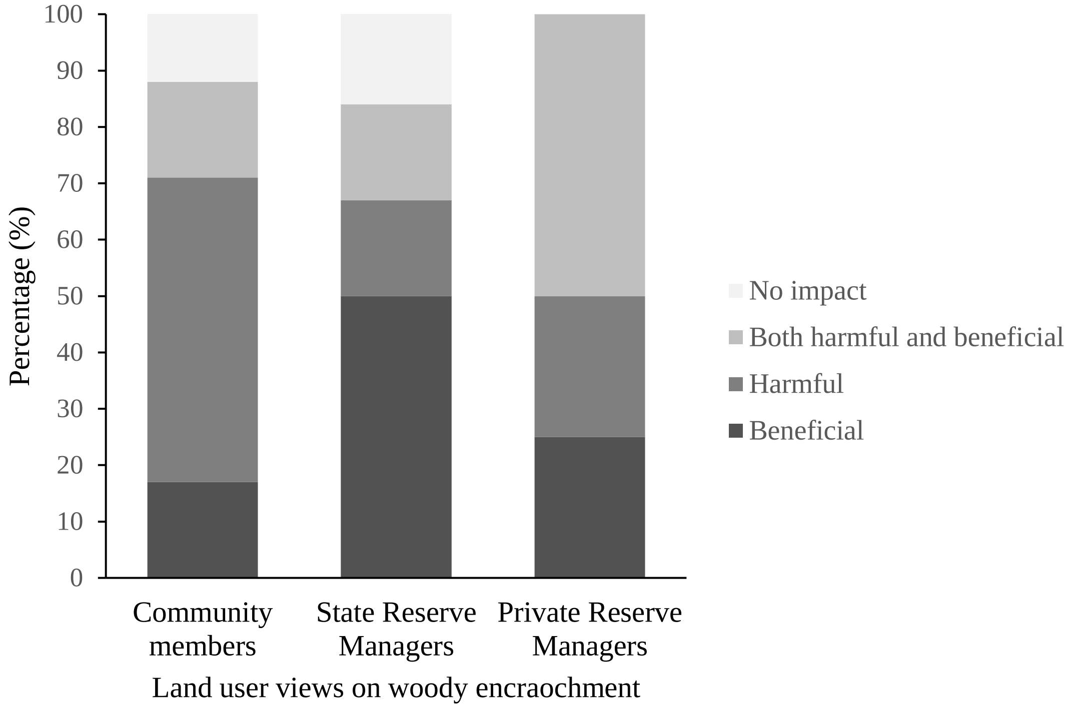

Figure 5.3: Land users' views on the impacts of woody encroachment. *(X^2 = 6.63; df = 6; p = 0.28)*

Tabel 5.3: Land user views of the harmful impacts of woody encroachment. *(X^2=25.31, df = 18, p = 0.27). Dash (-) refers to 0% reported cause.*

Harmful impacts of woody encroachment	Community members	State Reserve Managers	Private Reserve Managers	Mean
Reduces grass for grazing	29%	33%	50%	27.5%
Reduces water	13%	17%	25%	12.5%
Fear of wild animals &/or increased attacks by animals	25%	33%	-	20%
Fear of criminals	17%	17%	-	12.5%
Expensive to clear	8%	-	75%	12.5%
Spreads invasive alien species	8%	-	-	5%
Livestock gets lost in the bushes	13%	-	-	7.5%
Closes walking paths	17%	17%	-	12.5%
Replaces useful tree species	-	17%	-	5%
Guests cannot see the game	-	-	50%	5%

5.4.3 Costs of clearing

There were significant differences in the management of woody encroachment across the different land users (p = 0.01; X^2 = 11.44; df = 2). A minority (26%) of the respondents in the community cleared trees on their properties, and even fewer (13%) cleared trees outside their property. Of the six community members who cleared trees on their property, they spent, on average, R367/yr on clearing in the previous year (2017). In contrast, in the game reserves, much effort goes into the management of woody encroachment, particularly in the private reserves. Private game reserves spent an average of R293 751 the previous year on woody encroachment management, which consisted of both manual clearing and fire (Table 5.4). One of the reserves reported having spent an estimated R650 000 the previous year on woody encroachment management. The state game reserve spent R163 000 on burning the reserve as a measure to counteract woody encroachment. None of the reserves help clear or manage woody encroachment outside their reserves.

Table 5.4: Land users' management practices.

Land users' practices	Community members	State Reserve Managers	Private Reserve Managers	X^2, df, p value
Do you control woody encroachment on your property?	26%	67%	100%	11.44; 2; 0.01
Do you control woody encroachment in your area?	13%	0%	0%	2.21; 2; 1.0
Mean cost of management?	R367/yr -/+ R378	R163,000/yr -/+ R300 000	R293,751/yr	71.24; 13; <0.0001

5.5 Discussion

Most work examining the impact of woody encroachment on ecosystem services has focused on the biophysical and economic implications without examining land users perceptions (Eldridge *et al.*, 2011; Anadón *et al.*, 2014). This study presents one of the first efforts to understand perceptions around the drivers and impacts of woody encroachment. Insight into land users' perspectives can guide the design and implementation of policies or programmes that are consistent with the biophysical, social and economic needs of the people living in these social-ecological systems (Menzel and Teng, 2009).

Although perceptions of the causes of bush encroachment varied, all land users generally perceived Hluhluwe to be much woodier now than in the past (Figure 5.2). This is consistent with reports of woody encroachment occurring in the area and around the world (Wigley, Bond and Hoffman, 2009; Stevens, Lehmann, *et al.*, 2017). Land users also agreed that woody encroachment has a variety of mostly harmful impacts on their livelihoods, wellbeing and businesses.

The following quote echoes many of the impacts community members struggle with: "*there's nothing inherently wrong with trees but increased trees use more water. We need to sometimes cut down trees to get more water into the landscape. These thick areas hide wild animals such as leopard. Also, they kill grass and our livestock is life.*" Other key impacts on community members included fear of criminals hiding in the thick vegetation and closure of walking paths. This aligns with previous research in another part of South Africa where the rural community had negative attitudes towards woody encroachment, due to anxiety about wild animals harming their crops, loss of arable land and loss of landscape identity (Shackleton *et al.*, 2013). Cattle in rural communities have multiple purposes and their importance to people's livelihoods is captured in the statement "*our livestock is life*". Some of the goods and services provided by cattle include cash sales, providing a savings value (a traditional bank as one respondent called it), being slaughtered for rituals, food and manure (Shackleton *et al.*, 2005).

In a study done in the area a decade ago, the community cited increased wood for building/firewood and browse for animals as positive impacts, and less grass for grazing and difficulty clearing land for cultivation as the main negative impacts of woody encroachment (Wigley, Bond and Hoffman, 2009). This study did not find prominent benefits of encroachment in terms of extra wood supply. This is likely because many areas now have access to electricity, so that wood has become of less importance. Impacts on agricultural land also did not feature prominently, likely because many households (37%) have abandoned crop farming. Deagrarianisation in the area is partially due to the droughts of the past decade, changed value systems and rural emigration (Shackleton *et al.* 2013). Deagrarianisation in large parts of South Africa's rural areas has been linked to a significant increase in woody encroachment in abandoned cultivated fields (Shackleton *et al.*, 2013; Hoffman, 2014), and is likely to increase as rural emigration to urban areas increases (Christiaensen, De Weerdt and Todo, 2013).
Similarly, recent work by Russell and Ward, (2014) suggested that declining fuelwood collection (due to increased electrification of rural areas) may be contributing to woodland expansion in traditional rangelands in South Africa. When asked what the cause of woody encroachment was, one of the community members responded, "*We used to use trees build fences, houses, kraals and firewood. Now we used bricks, wire and electricity*". Our interviews confirmed that collection of fuelwood in the study area is declining because many households increasingly rely on electricity for their energy needs. According to StatsSA (2018), 92.3% of the area had electricity in 2011 as compared to 28.7% a decade earlier. Only two out of the 30 households (6.7%) in our survey still relied on firewood as their primary source of energy. Most households collected firewood only if there was going to be a traditional ceremony taking place and large amounts of cooking needed to be done.

In contrast to community members, private game reserve managers were mainly concerned by impacts on their business through trees blocking guests from seeing animals, reduction of grass for grazing by wildlife, and the high cost of clearing trees. Game visibility is an important factor for tourists returning to a game reserve (Gray and Bond, 2013). In a survey of marketing strategies, beliefs and practices of private game reserves in southern Africa, Buckley and Mossaz (2018) found that private game reserves prioritize marketing of game viewing opportunities, followed by luxury, exclusivity and conservation. Woody encroachment also negatively impacts tourism by changing the biodiversity of the area, as certain animals, e.g. cheetahs, white rhino and certain bird species, need open areas to thrive (Maciejewski and Kerley, 2014). This negatively impacts tourism as many guests, especially international tourists, mostly want to see mega-herbivores and large carnivores (Lindsey *et al.*, 2007). Many private game reserves target international tourists from first world countries, and focus on having a few guests that pay high prices (Magole and Magole, 2011). This explains why one of reserves spent an estimated R650 000 on burning and manually clearing trees. Most of the clearing on these reserves was focused on heavily encroached areas on the popular tourist routes. For example, one of the reserves specifically invested in clearing around their gate and towards the lodges so guests could see game as they enter their premises. The less travelled routes were seldom cleared because of the high costs. Another reserve was using some of the pesticide provided by the government to clear invasive alien species to kill and dry the encroaching trees before burning them, because of the high costs of manual clearing. Another private reserve has started experimenting with fire storms (high intensity fires) because historic fire frequencies are no longer enough to hold back woody encroachment.

In contrast to community members and private reserve managers, a majority of the state game reserve managers thought woody encroachment was beneficial or had no impact on their business. Unlike private game reserves, the state reserves' objectives centre more exclusively on conservation. Consequently, they manage the landscape to maintain historic patterns and processes. They use controlled burning to simulate natural fire patterns and to maintain the open savanna ecosystem. Case and Staver (2017) examined woody encroachment in the state reserve from 2007 to 2014 across different fire frequencies and found that historic fire frequencies are no longer capable of mitigating woody encroachment in this reserve. This research has yet to filter up to management. Hluhluwe iMfolozi Game Reserve has a large number of elephant and managers are aware that they also help control woody encroachment. Bark-stripping and uprooting of trees by elephants can result in mortality of adult trees and seedlings (O'Connor *et al.*, 2007; O'Connor, Puttick and Hoffman, 2014). Stevens *et al.* (2016) found that elephants had a significant impact in low rainfall (MAP > 650 mm) savannas compared to high rainfall areas. Given that Hluhluwe occurs in a high rainfall zone, this may explain the prevalence of woody encroachment despite the high number of elephants.

5.6 IMPLICATIONS FOR MANAGEMENT AND CONCLUSION

The results highlight the need to manage woody encroachment to reduce impacts experienced by community members and in private game reserves. In South Africa, a lot of work and resources has gone into clearing invasive alien species through the state-funded Working for Water programme, and into understanding their influence on different land users in South Africa (van Wilgen and Biggs, 2011; Urgenson, Prozesky and Esler, 2013; Van Wilgen, Davies and Richardson, 2014; Shackleton, Le Maitre and Richardson, 2015). However, little research and resources have gone into understanding the impacts of woody encroachment (Nackley *et al.*, 2017). If similar clearing programmes were developed to address woody encroachment, we need to understand and align policies with land users perceptions, values and needs.

This research suggests that most of the land users would welcome a state-supported clearing program. In one of the villages, woody encroachment had become so bad that it prompted the initiation of a local state programme, similar to the Working for Water programme, to clear trees. In that village, one respondent noted "*There has been some clearing in the area. Cleared areas are no longer scary. Grass has come back in those areas with cows benefitting. It provides safety. People used to get mugged in the forest. Couldn't just walk alone in the thick areas.*" Especially if it were done strategically, clearing would have important benefits, because although there has been a reduced use of trees, people still use trees intermittently.

Private game reserves spend a lot of money on clearing trees and would also benefit from a state tree clearing programme, and could potentially help fund such a program from their tourism revenue. These reserves also provide opportunities for doing research on the effectiveness of different clearing techniques. All the reserves in this study were trying different strategies to manage woody encroachment, but none of the results are being studied and published.

According to the Food and Agriculture Organization, landscapes with >10% tree cover constitute forests, and therefore qualify for reforestation projects such as Reducing Emissions form Deforestation and Forest Degradation (REDD+) and other carbon emission reduction projects (Parr *et al.*, 2014). Many of these projects target developing countries so they can earn certified emission reduction credits which could be sold/traded to industrialized countries. This study underscores the calls of other authors to be careful with applying the FAO's definition of savanna, and for carbon emission projects to consider with more care where they implement these projects. Twenty five percent of Africa would qualify for REDD+ projects if forests are defined as areas with >10% tree cover (Parr *et al.*, 2014). Misclassification of savannas as forests or degraded forests threatens the livelihoods of large numbers of people (Bond, 2016). One fifth of the global population, many of them poor, relies on grassy systems for their livelihoods (Parr *et al.*, 2014). If woody cover in these areas was expanded it would have substantial social and ecological impacts (Veldman *et al.*, 2015), as underscored by this study where cattle farming and wildlife tourism form a large part of people's identities and livelihoods.

5.7 REFERENCES

Anadón, J. D. *et al.* (2014) 'Effect of woody-plant encroachment on livestock production in North and South America.', *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences, 111(35), pp. 12948–53. doi: 10.1073/pnas.1320585111.

Archer, S. R. and Predick, K. I. (2014) 'An ecosystem services perspective on brush management: research priorities for competing land-use objectives', *Journal of Ecology*. Edited by F. Maestre. Blackwell Publishing Ltd, 102(6), pp. 1394–1407. doi: 10.1111/1365-2745.12314.

Bond, W. J. (2016) 'Ancient grasslands at risk', *Science*, 351(6269), pp. 120–122. doi: 10.1126/science.aad5132.

Briggs, J. M. *et al.* (2005) 'An Ecosystem in Transition: Causes and Consequences of the Conversion of Mesic Grassland to Shrubland', *BioScience*. American Institute of Biological Sciences, 55(3), p. 243. doi: 10.1641/0006-3568(2005)055[0243:AEITCA]2.0.CO;2.

Cardinale, B. J. *et al.* (2012) 'Biodiversity loss and its impact on humanity.', *Nature*, 486(7401), pp. 59–67. doi: 10.1038/nature11148.

Carpenter, S. R. *et al.* (2009) 'Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment.', *Proceedings of the National Academy of Sciences of the United States of America*, 106(5), pp. 1305–12. doi: 10.1073/pnas.0808772106.

Christiaensen, L., De Weerdt, J. and Todo, Y. (2013) 'Urbanization and poverty reduction: the role of rural diversification and secondary towns', *Agricultural Economics*, 44(4–5), pp. 435–447. doi: 10.1111/agec.12028.

Daskin, J. H., Stalmans, M. and Pringle, R. M. (2016) 'Ecological legacies of civil war: 35-year increase in savanna tree cover following wholesale large-mammal declines', *Journal of Ecology*. Edited by L. Gomez-Aparicio, 104(1), pp. 79–89. doi: 10.1111/1365-2745.12483.

Diaz, S. *et al.* (2004) 'The plant traits that drive ecosystems: Evidence from three continents', *Journal of Vegetation Science*. Blackwell Publishing Ltd, 15(3), pp. 295–304. doi: 10.1658/1100-9233(2004)015[0295:TPTTDE]2.0.CO;2.

Eldridge, D. J. *et al.* (2011) 'Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis.', *Ecology letters*, 14(7), pp. 709–22. doi: 10.1111/j.1461-0248.2011.01630.x.

Gray, E. F. and Bond, W. J. (2013) 'Will woody plant encroachment impact the visitor experience and economy of conservation areas?', *Koedoe*, 55(1), pp. 1–9. doi: 10.4102/koedoe.v55i1.1106.

Grossman, J. J. (2015). Ecosystem service trade-offs and land use among smallholder farmers in eastern Paraguay. *Ecology and Society*, *20*(1), art19. http://doi.org/10.5751/ES-06953-200119.

Hamann, M., Biggs, R. and Reyers, B. (2015) 'Mapping social–ecological systems: Identifying "green-loop" and "red-loop" dynamics based on characteristic bundles of ecosystem service use', *Global Environmental Change*, 34, pp. 218–226. doi: 10.1016/j.gloenvcha.2015.07.008.

Higgins, S. I., Shackleton, C. M. and Robinson, E. R. (1999) 'Changes in Woody Community Structure and Composition under Contrasting Landuse Systems in a Semi', *Journal of*

Biogeography, 26(3), pp. 619–627. Available at: https://www.jstor.org/stable/pdf/2656147.pdf?refreqid=excelsior%3A79b3410e731dd3505e9d58ff224af70e (Accessed: 29 November 2018).

Hoffman, M. T. (2014) 'Changing Patterns of Rural Land Use and Land Cover in South Africa and their Implications for Land Reform', *Journal of Southern African Studies*, 40(4), pp. 707–725. doi: 10.1080/03057070.2014.943525.

Honda, E. A. *et al.* (2016) 'Woody encroachment and its consequences on hydrological processes in the savannah.', *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*. The Royal Society, 371(1703), pp. 115–133. doi: 10.1098/rstb.2015.0313.

Huxman, T. E. *et al.* (2005) 'Ecohydrological implications of woody encroachment', *Special Feature Ecology*, 86(2), pp. 308–319.

King, E., Cavender-Bares, J., Balvanera, P., Mwampamba, T. H., & Polasky, S. (2015). Trade-offs in ecosystem services and varying stakeholder preferences: evaluating conflicts, obstacles, and opportunities. *Ecology and Society, 20*(3), art25. http://doi.org/10.5751/ES-07822-200325.

Lawes, M. J., Macfarlane, D. M. and Eeley, H. A. C. (2004) 'Forest landscape pattern in the KwaZulu – Natal midlands , South Africa : 50 years of change or stasis ?', pp. 613–623.

Lehmann, C. E. R. *et al.* (2014) 'Savanna Vegetation-Fire-Climate Relationships Differ Among Continents', *Science*, 548(January), pp. 548–552. doi: 10.1126/science.1247355.

Leslie, P. and McCabe, J. T. (2013) 'Response Diversity and Resilience in Social-Ecological Systems.', *Current anthropology*. NIH Public Access, 54(2), pp. 114–143. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24855324 (Accessed: 9 July 2018).

Lindsey, P. A. *et al.* (2007) 'Wildlife viewing preferences of visitors to protected areas in South Africa: Implications for the role of ecotourism in conservation', *Journal of Ecotourism*, 6(1), pp. 19–33. doi: 10.2167/joe133.0.

Loreau, M. *et al.* (2001) 'Biodiversity and ecosystem functioning: current knowledge and future challenges.', *Science (New York, N.Y.)*. American Association for the Advancement of Science, 294(5543), pp. 804–8. doi: 10.1126/science.1064088.

Maciejewski, K. and Kerley, G. I. H. (2014) 'Understanding tourists' preference for mammal species in private protected areas: Is there a case for extralimital species for ecotourism?', *PLoS ONE*, 9(2). doi: 10.1371/journal.pone.0088192.

Magole, L. I. and Magole, L. (2011) 'Revisiting Botswana's High-Value, Low-Volume Tourism', *Tourism Analysis*, 16(2), pp. 203–210. doi: 10.3727/108354211X13014081270486.

McNally, C. G. *et al.* (2016) 'Stakeholder perceptions of ecosystem services of the Wami River and estuary', *Ecology and Society*, 21(3). doi: 10.5751/ES-08611-210334.

Menzel, S. and Teng, J. (2009) 'Ecosystem Services as a Stakeholder-Driven Concept for Conservation Science', *Conservation Biology*, 24(3), pp. 907–909. doi: 10.1111/j.1523-1739.2009.01347.x.

Millennium Ecosystem Assessment (2005) *Ecosystems and human well-being: synthesis*. Washington, DC.

Moustakas, A. *et al.* (2010) 'Learning new tricks from old trees : revisiting the savanna question', *Frontiers of biogeography*, 2(2004), pp. 47–53.

Mugasi, S. K., Sabiiti, E. N. and Tayebwa, B. M. (2000) 'The economic implications of bush encroachment on livestock farming in rangelands of Uganda', *African Journal of Range & Forage Science*. Taylor & Francis Group , 17(June 2014), pp. 64–69. doi: 10.2989/10220110009485741.

Nackley, L. L. *et al.* (2017) 'The Nebulous Ecology of Native Invasions', *Trends in Ecology & Evolution*, 32(11). doi: 10.1016/j.tree.2017.08.003.

O'Connor, T. G. *et al.* (2007) 'A functional hypothesis of the threat of local extirpation of woody plant species by elephant in Africa', *Biological Conservation*, 136(3), pp. 329–345. doi: 10.1016/j.biocon.2006.12.014.

O'Connor, T. G., Puttick, J. R. and Hoffman, M. T. (2014) 'Bush encroachment in southern Africa : changes and causes', *African Journal of Range and Forage Science*, 31(October), pp. 67–88. doi: 10.2989/10220119.2014.939996.

Parr, C. L. *et al.* (2014) 'Tropical grassy biomes: misunderstood, neglected, and under threat', *Trends in Ecology & Evolution*, 29(4), pp. 205–213. doi: 10.1016/j.tree.2014.02.004.

Reid, W. V. *et al.* (2010) 'Earth System Science for Global Sustainability: Grand Challenges', *Science*, 330(November), pp. 916–917. doi: 10.1126/science.1196263.

Russell, J. M. and Ward, D. (2014) 'Remote sensing provides a progressive record of vegetation change in northern KwaZulu-Natal, South Africa, from 1944 to 2005', *International Journal of Remote Sensing*, 35(3), pp. 904–926. doi: 10.1080/01431161.2013.873154.

Sankaran, M. *et al.* (2005) 'Determinants of woody cover in African savannas.', *Nature*, 438(7069), pp. 846–9. doi: 10.1038/nature04070.

Scheffer, M. *et al.* (2001) 'Catastrophic shifts in ecosystems.', *Nature*, 413(6856), pp. 591–596. doi: 10.1038/35098000.

Shackleton, C. *et al.* (2005) 'The contribution and direct-use value of livestock to rural livelihoods in the Sand River catchment, South Africa', *African Journal of Range & Forage Science*. Taylor & Francis Group , 22(2), pp. 127–140. doi: 10.2989/10220110509485870.

Shackleton, R. *et al.* (2013) 'Deagrarianisation and forest revegetation in a biodiversity hotspot on the Wild Coast, South Africa.', *PloS one*, 8(10), p. e76939. doi: 10.1371/journal.pone.0076939.

Shackleton, R. T., Le Maitre, D. C. and Richardson, D. M. (2015) 'Stakeholder perceptions and practices regarding Prosopis (mesquite) invasions and management in South Africa', *AMBIO*, 44, pp. 569–581. doi: 10.1007/s13280-014-0597-5.

Skowno, A. L. *et al.* (2017) 'Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers', *Global Change Biology*, 23(6), pp. 2358–2369. doi: 10.1111/gcb.13529.

Stevens, N. *et al.* (2016) 'Woody encroachment over 70 years in South African savannahs: overgrazing, global change or extinction aftershock?', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1703), p. 20150437. doi: 10.1098/rstb.2015.0437.

Stevens, N. *et al.* (2017) 'Savanna woody encroachment is widespread across three continents', *Global Change Biology*, 23(1). doi: 10.1111/gcb.13409.

Thondhlana, G., Vedeld, P. and Shackleton, S. (2012) 'Natural resource use, income and dependence among San and Mier communities bordering Kgalagadi Transfrontier Park, southern Kalahari, South Africa', *International Journal of Sustainable Development & World Ecology*. Taylor & Francis , 19(5), pp. 460–470. doi: 10.1080/13504509.2012.708908.

Troell, M. *et al.* (2005) *Regime shifts and ecosystem services in Swedish coastal soft bottom habitats: when resilience is undesirable*. Available at: https://dlc.dlib.indiana.edu/dlc/bitstream/handle/10535/3083/30.pdf?sequence=1&isAllowed=y (Accessed: 5 November 2018).

Twine, W. *et al.* (2003) 'Consumption and direct-use values of savanna bio-resources used by rural households in Mametja, a semi-arid area of Limpopo province, South Africa', *South African Journal of Science*, 99, pp. 467–473.

Urgenson, L. S., Prozesky, H. E. and Esler, K. J. (2013) 'Stakeholder perceptions of an ecosystem services approach to clearing invasive alien plants on private land', *Ecology and Society*, 18(1). doi: 10.5751/ES-05259-180126.

Veldman, J. W. *et al.* (2015) 'Toward an old-growth concept for grasslands, savannas, and woodlands', *Frontiers in Ecology and the Environment*, 13(3), pp. 154–162. doi: 10.1890/140270.

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. doi: 10.1111/j.1365-2028.2008.01051.x.

Wigley, B. J., Bond, W. J. and Hoffman, M. T. (2010) 'Thicket expansion in a South African savanna under divergent land use: Local vs. global drivers?', *Global Change Biology*, 16(3), pp. 964–976. doi: 10.1111/j.1365-2486.2009.02030.x.

van Wilgen, B. W. and Biggs, H. C. (2011) 'A critical assessment of adaptive ecosystem management in a large savanna protected area in South Africa', *Biological Conservation*, 144(4), pp. 1179–1187. doi: 10.1016/j.biocon.2010.05.006.

Van Wilgen, B. W., Davies, S. J. and Richardson, D. M. (2014) 'Invasion science for society: A decade of contributions from the centre for invasion biology', *South African Journal of Science*, 110(7–8), pp. 1–12. doi: 10.1590/sajs.2014/a0074.

Ye, Y., Bryan, B. A., Zhang, J., Connor, J. D., Chen, L., Qin, Z., & He, M. (2018). Changes in land-use and ecosystem services in the Guangzhou-Foshan Metropolitan Area, China from 1990 to 2010: Implications for sustainability under rapid urbanization. *Ecological Indicators*, *93*, 930–941. http://doi.org/10.1016/J.ECOLIND.2018.05.031

CHAPTER 6: CONCLUSION

6.1 INTRODUCTION

Human behaviour has modified the earth's processes in ways that threaten its ability to keep providing us with the ecosystem services necessary to sustain mankind and other species (Millennium Ecosystem Assessment, 2005). These changes to the planet have led to the increased prevalence of regime shifts - large and persistent changes in the structure and function of ecosystems and the broader social-ecological systems in which they are embedded – that can be either gradual or abrupt. Regime shifts are challenging to manage due to difficulties in predicting regime shifts, their considerable impacts on ecosystem services and human wellbeing, and the costs of reversing regime shifts (Crépin *et al.*, 2012). As a consequence, there has been a growing interest in predicting regime shifts and detecting early warning signs of regime shifts at different scales.

This dissertation focuses on improving our understanding of regime shifts, specifically from a broader social-ecological perspective, and how such shifts might be monitored and managed, by investigating the example of woody encroachment in South Africa. Woody encroachment has been a problem in South African savannas for nearly a century, with managers and researchers simultaneously trying to understand savanna ecology and the drivers of woody encroachment, due to its impacts on ecosystem services and human well-being.

This chapter revisits the key research questions set out in Chapter 1, and synthesizes the main findings and contributions from each research chapter. I then step back to discuss the overall insights from the study, before reflecting on the limitations and future directions emerging from the research.

6.2 SUMMARY OF KEY FINDINGS

The four research chapters (Chapters 2-5) each yielded a number of insights in terms of the key research questions outlined in Chapter 1. This section summarizes these findings, before reflecting on the overall insights across the study.

Q1. What are the ecological and social processes underlying woody encroachment, and how do they interact to drive encroachment? (Chapter 2)

Chapter 2 presents a review of woody encroachment as a social-ecological regime shift. The chapter undertakes a systems analysis of woody encroachment, identifying key drivers, feedbacks, thresholds and leverage points using the regime shifts analysis framework (Biggs, Peterson and Rocha, 2018). The social and ecological processes underlying woody encroachment are highlighted, and how changes in these processes alter the feedbacks in arid and mesic savanna systems. This analysis presents one of very few papers to characterize and describe woody encroachment as a social-ecological regime shift.

The analysis highlights that both at a local and global scale, woody encroachment may ultimately be linked to growing human populations. At a global scale, growing human populations and urbanization are linked to increased demand for livestock products and increasing carbon dioxide emissions, given current consumption practices. At a local scale, fire suppression, which is also linked to growing human populations and urbanization (Archibald *et al.*, 2009), increases the likelihood of woody encroachment. The fire feedback is the main reinforcing feedback that maintains the grassy regime in mesic savannas, while water limits tree establishment in arid savannas (Sankaran *et al.*, 2005).

The novelty of this analysis is that it systematically characterizes the system, in terms of both social and ecological processes, providing a useful way to understand the diverse social-ecological interactions and feedbacks that underlie encroachment. The effective management of savanna systems requires understanding and manipulating the drivers and feedbacks in the system, taking account of possible delays in the effect of some processes. Causal loop diagrams can help managers identify leverage points – places where a change in the system will produce the most gain.

This analysis highlighted that the key leverage points for managing woody encroachment in savanna systems include manipulation of fire (increasing either the frequency or the intensity), maintaining a high number of browsers in the system (goats and elephants) and strategic manual clearing linked to periods of higher and lower rainfall (Smit, 2004; Angassa and Oba, 2009; Smit *et al.*, 2016; Skowno *et al.*, 2017). At a broader scale, increased carbon emissions and variations in floods and droughts will likely enhance the risk of woody encroachment. Influencing consumption preferences and practices in ways that reduces demand for livestock as well as bringing down carbon dioxide emissions, could also play a key role in maintaining open savanna systems in the future.

Q2. Can we use readily available remotely sensed data to assess and monitor encroachment across different land uses? (Chapter 3)

Chapter 3 uses Landsat TM imagery to quantify the extent of woody encroachment in the Hlabisa district of South Africa over a period of 26 years. This area comprises of two main land use practices: a state-owned conservation area (Hluhluwe-iMfolozi Park) with mega-herbivores and a high fire frequency, and communal areas that comprise mainly of small-scale subsistence farming with cattle and goats and have a lower fire frequency.

We found highly significant increases in tree cover across all land uses, with land use practice impacting the rate of increase in woody cover. The extent of encroachment was larger in the conservation area than in the communal areas, but recently the rate of encroachment in the communal areas exceeds that of the conservation areas. This is most likely due to reduced tree harvesting in recent years, associated with the increased electrification of the area (Chapter 5; Russell and Ward, 2014). The fact that encroachment is occurring across all land uses, suggests that global drivers, likely increased atmospheric CO_2, rather than differences in local management practices, are currently the main drivers of encroachment.

This study provides support for the use of Landsat imagery to monitor and assess woody encroachment. The majority of studies estimating the extent of woody encroachment to date have used field studies and aerial imagery. The results of this study produced comparable results to studies using aerial images. The goal for monitoring is to use easily accessible data with simple methods (e.g., not requiring advanced modelling), and quick analyses to aid managers. The main prerequisite for using Landsat is that careful radiometric corrections need to be done on the images, and appropriate images need to be selected based on rainfall records in order to minimize phenology effects.

Q3. Does woody encroachment conform to the statistical properties of a regime shift, and can we use these properties to monitor woody encroachment regime shifts? (Chapter 4)

Chapter 4 tests whether the woody encroachment detected in Chapter 3 conforms to the statistical properties of a regime shift. I used sequential t-test analysis of regime shifts (STARS) to test whether woody encroachment in Hlabisa in recent decades constitutes a regime shift. I then calculated spatial autocorrelation over the 26-year time period to establish whether there was early warning of this regime shift prior to it occurring.

I demonstrate that woody encroachment occurring in the Hlabisa district represents a regime shift, and estimate that the shift occurred in 2009. I also found evidence of increasing spatial autocorrelation from 1990 – 2006, signifying that there was early warning of this regime shift prior to its occurrence.

This study demonstrates the first application of STARS to detect whether woody encroachment constitutes a regime shift, rather than simply an increase in tree cover data. This has practical management implications because once managers know a regime shift has occurred, they need to adopt different management strategies to either sustain or reverse woody cover. This research suggests that remote sensing data could be used to detect woody encroachment regime shifts from readily available remote sensing data with limited temporal timespans, and spatial autocorrelation could serve as a monitoring indicator for approaching thresholds.

Q4. How are stakeholders associated with different land uses impacted by woody encroachment? (Chapter 5)

Chapter 5 investigates the impact of woody encroachment on local land users and their livelihoods, and how this in turn influences their management strategies. Semi-structured questionnaires were used to explore how rural communities, private and state game reserve managers perceive woody encroachment, how it impacts them or their businesses, and the costs of reversing woody encroachment on their properties.

All land users in this study perceived woody encroachment to be occurring in the Hlabisa area. Results indicate that rural households and private game reserves are significantly impacted by woody encroachment, through on the reduction of grazing capacity, high clearing costs and fear of criminals and animals hiding in the thick vegetation. A change of lifestyle and access to electricity in the communities were the most cited causes of encroachment, while reserve managers cited carbon dioxide and increased variability in droughts and floods as the main causes. Not being able to burn mesic savannas due to the drought, abandoning farming because there is no water and rural migration were other factors that were seen to play an important role in woody encroachment in the area.

Private game reserves invested the most in clearing trees and on trying different strategies to manage woody encroachment because game viewing and customer satisfaction are an important part of their business. The cost of clearing was too much for the already struggling community and therefore very few people cleared trees in the villages. State game reserves mainly focus on maintaining the system according to historic patterns and processes. With increasing carbon dioxide concentrations being linked and suggested as the main driver of current woody encroachment across the globe (Wigley, Bond and Hoffman, 2010; Moncrieff *et al.*, 2014; Stevens *et al.*, 2016; Archer *et al.*, 2017), this strategy may no longer be viable. One of the private game reserves has already started experimenting with fire storms because the historic fire regime no longer contains encroachment.

This study presents one of only a handful of studies that have investigated the perceptions of land users to woody encroachment in South Africa, and the only one that has linked it back to management strategies. Perceptions of whether woody encroachment is harmful or beneficial may explain why the private reserve managers are investing more in managing woody encroachment. Differences in management strategies are often due to differences in worldviews and values even if the land use is the same (Ellis and Swift, 1988).

6.3 KEY INSIGHTS RELEVANT TO MANAGEMENT OF WOODY ENCROACHMENT

Reflecting on insights and connections across the four research papers, a number of cross-cutting insights emerge that are particularly relevant to the management of woody encroachment.

One key insight from this study is the extent to which the worldviews of managers and their understanding of encroachment influence practical management strategies. Chapter 5 revealed that in the state game reserves, half the managers felt woody encroachment is beneficial, and the other half thought it either had no impact or had negative impacts. As a consequence the reserve didn’t have many woody encroachment mitigation measures even though all managers said encroachment was increasing. In contrast, private game reserve managers had negative views of woody encroachment and were not only burning their reserves; they were manually removing trees and chemically killing them. The state reserve managers were managing the reserve to mimic past savanna dynamics – even though they acknowledged increasing carbon dioxide as a possible driver of the encroachment. With increasing carbon dioxide concentrations being suggested as the main driver of current woody encroachment across the globe (Wigley, Bond and Hoffman, 2009; Buitenwerf, Bond, Stevens and Trollope, 2012; Moncrieff *et al.*, 2014; Archer *et al.*, 2017), mimicking past savanna dynamics through for instance past fire regimes may no longer be sufficient to mitigate woody encroachment. In a recent study by Case and Staver, (2017) on research done in this park, they found that historic fire frequencies are no longer capable of maintaining open systems. This research has not yet resulted in any changes to the management strategy of the state park.

The changes being experienced in savanna systems suggests that more adaptive, experimental approaches to management of encroachment may be required (Biggs *et al.*, 2015). One of the private game reserves managers utilizes systems thinking and adaptive management to manage the various uncertainties they are currently facing. They are currently experimenting with multiple methods of dealing with woody encroachment. The state reserve managers have a conventional view of the ecosystems (where changes to ecosystems lead to gradual, predictable effects) and still operate under the assumption that the previous management strategies will continue to work in maintaining the system in a grassy regime. During the interviews I asked what they were planning to do with the large amount of seedlings and saplings covering most of the park after the drought limited prescribed burning. There was no sense of urgency or concern compared to the private reserve managers. The private game reserve managers, whether it was areas they take tourists to or not, were concerned about the state of the whole reserve and excited to experiment with different methods to manage woody encroachment.

Broader social and economic changes in South Africa are also affecting encroachment and need to be considered in strategies to contain it, particularly in the rural areas. One of the Sustainable Development Goals (SDGs) is to ensure access to affordable, reliable, sustainable and modern energy for all. Since the fall of the Apartheid government in South Africa, the Reconstruction and Development Programme (RDP) was initiated by the democratic government to focus on the provision of services to the poor communities, with one of their goals the electrification of 2.5 million new households (Wehner, 2000). However, electrification is reducing tree harvesting, which is a balancing feedback loop in savannas; reduced tree harvesting is therefore linked to increases in woody encroachment (Smit, 2004; Angassa and Oba, 2009; Russell and Ward, 2014). In South Africa, most of the population that currently have a high dependence on wood based ecosystem services reside in savanna systems(Hamann, Biggs and Reyers, 2015), which puts these systems at risk of woody encroachment as electrification and other development initiatives reach these areas. A large amount of Africa uses wood for energy, and electrification will therefore likely have repercussions on the structure of savannas across Africa (Vermeulen, Campbell and Mangono, 2000; Egeru, 2014; Cerutti *et al.*, 2015).

Urbanization and abandonment of farming is further aggravating encroachment. Reported increases in the abandonment of farming practices and reduced harvesting rates across the country were also reflected in this study (Hoffman, 2014; Russell and Ward, 2014). Abandonment of land in rural areas and emigration to the cities is mainly a result of large numbers of young people moving to urban areas in search of employment, education and other opportunities outside of farming (Baiphethi and Jacobs, 2009). The resulting reduced dependence and direct use of provisioning ecosystem services such as fuelwood in rural communities has been linked to the increased prevalence of woody encroachment (Hoffman, 2014). To contain encroachment in these areas we need to find ways of utilizing excess wood and possibly create markets to incentivise the removal of excess trees.

Using the social-ecological regime shifts analysis presented in this thesis would greatly benefit managers in their pursuit of limiting woody encroachment on their properties. Using Landsat imagery together with spatial autocorrelation and STARS could serve as a monitoring indicator for approaching thresholds and significantly enhance woody encroachment management. Once managers know a potential regime shift is approaching or has occurred, a broader regime shift analysis, including the construction of a causal loop diagram, would then be needed to identify which drivers and feedbacks have changed and therefore need weakening or strengthening to manage the system for desired outcomes.

6.4 FUTURE RESEARCH DIRECTIONS

Although the notion that ecosystems can undergo regime shifts has been recognized for some time (Scheffer *et al.*, 2001; Anderies, Janssen and Walker, 2002; Folke *et al.*, 2004; D'Odorico, Okin and Bestelmeyer, 2012), most research and management practices still do not reflect this. Most of the work on ecological regime shifts has focused on the direct ecological drivers of these shifts. More research needs to be done on how various social aspects of the system influences the potential for regime shifts - including the worldviews of the managers of systems. Understanding the broader social-ecological system in which regime shifts occur is crucial for managing the system in a way that ensures resilience of ecosystem services and human wellbeing. Likewise, research on societies have adapted or transformed in response to regime shifts is missing in the literature. In the Hlabisa region, for example, livestock farmers have gone transformed to game farmers and private game reserves. Was this a result of the woody encroachment or other drivers?

To understand regime shifts you need to understand the system – both the social and ecological - and the long term data required for this is a problem. In this study I used remote sensing data to examine changes in tree cover (Chapter 2 and 3). Over a 26-year period, only 11 images were cloud free and could be used for the study. Fortunately, the changes were large enough, and the regime shift detection methods I used could detect regime shifts with a minimum of 10 time series points. Nevertheless, further work is needed to advance regime shift monitoring and detection methods in real-world management settings.

Access to data on the social component of systems can be difficult. I had difficulty accessing reserve managers due to their busy schedules, and was only able to meet with some of them after an official introduction from the park ecologist. Access to private game reserves managers was even tougher, which contributed to my small sample size. Any work in communal areas under traditional government requires permission for the chiefs, which can also be a difficult and long process. While interviews with managers and community members may be costly and time consuming, understanding the perspectives of land users and managers, how they interact, and how they manage their land is crucial for understanding changes in ecosystems. Similarly, it is also crucial to know how land management practices change over time and what the driving forces behind these changes are.

With regards to woody encroachment, very little research has gone into understanding the impacts of urbanization (e.g., policies that affect land management, rural emigration and the development of rural areas) on woody encroachment, and also how woody encroachment has impacted land use. For example, in the Hlabisa area, most of the commercial livestock farmers have gone into game farming or formed conglomerates of private game reserves. It would be interesting to know if woody encroachment played a role in this change in land use, as it could point to a missing feedback in the system that has not been explored.

With increased atmospheric carbon dioxide and changes in the frequency of droughts and floods, many of the Earth's ecosystems will be functioning in uncharted territory. Research into how different drivers influence key system variables is important to inform decisions with regard to whether it is feasible to avoid or reverse regime shifts, or whether effort would be better invested in directing the transformation of the system onto a favourable path. To explore the latter, research should also focus on ways to best navigate transformation of systems, for instance shifts from grassy to woody savannas. In many cases, we know what the alternate regime is, and we could start investigating ways to make the best of the new regime, and especially, ways in which to support transformation of livelihoods associated with each regime.

6.5 Closing reflections

The original aim of this research was to model and map woody encroachment across South Africa. I then realised that a deeper understanding of the system is necessary before I attempt this. Having done the research to better understand woody encroachment regime shifts in savannas, I would be hesitant to recommend such a task. A lot of contradicting research on the drivers of woody encroachment has been reported depending on the scale of the research (Wigley, Bond and Hoffman, 2010; Skowno *et al.*, 2017; Venter, Cramer and Hawkins, 2018). Woody encroachment has been reported to be negligible or reversed in conservation areas with elephants, whereas I found woody encroachment to be increasing in my study even in the conservation area that had a large elephant population. This highlights that even with just ecological drivers it is difficult to predict woody encroachment.

A key insight from my research is that one cannot model regime shifts based only on the quantifiable variables in the systems. How managers view the SES they are managing, how much experimentation and learning they do, the turnover in management, and the overall development trends in the region all play an important role in the functioning of systems. Interactions between land users at different geographic scales and authority levels are complex, and changes within them may be difficult or impossible to predict.

Nevertheless, given the importance of grassy savanna systems for a variety of ecosystem services, it is important to quantify and predict woody encroachment on a scale that is useful for managers. This study highlights that early warning/resilience indicators are a viable and useful approach, provided one keeps in mind the many missing aspects, especially on the social dimension. This study therefore underscores the value of making hyperspectral remote sensing data easily accessible to monitor and quantify ecosystem changes.

6.6 References

Anderies, John M., Marco A. Janssen, and Brian H. Walker. 2002. "Grazing Management, Resilience, and the Dynamics of a Fire-Driven Rangeland System." *Ecosystems* 5 (1): 23–44. https://doi.org/10.1007/s10021-001-0053-9.

Angassa, Ayana, and Gufu Oba. 2009. "Bush Encroachment Control Demonstrations in Southern Ethiopia: 1. Woody Species Survival Strategies with Implications for Herder Land Management." *African Journal of Ecology* 47: 63–76. https://doi.org/10.1111/j.1365-2028.2007.00919.x.

Archer, Steven R., Erik M. Andersen, Katharine I. Predick, Susanne Schwinning, Robert J. Steidl, and Steven R. Woods. 2017. "Woody Plant Encroachment: Causes and Consequences." In , 25–84. Springer, Cham. https://doi.org/10.1007/978-3-319-46709-2_2.

Archibald, Sally, David P. Roy, Brian W. van Wilgen, and Robert J. Scholes. 2009. "What Limits Fire? An Examination of Drivers of Burnt Area in Southern Africa." *Global Change Biology* 15: 613–30. https://doi.org/10.1111/j.1365-2486.2008.01754.x.

Baiphethi, M N, and P T Jacobs. 2010. "The Contribution of Subsistence Farming to Food Security in South Africa." https://doi.org/10.1080/03031853.2009.9523836.

Biggs, Reinette Oonsie, Clint Rhode, Sally Archibald, Lucky Makhosini Kunene, Shingirirai S. Mutanga, Nghamula Nkuna, Peter Omondi Ocholla, and Lehlohonolo Joe Phadima. 2015. "Strategies for Managing Complex Social-Ecological Systems in the Face of Uncertainty: Examples from South Africa and Beyond." *Ecology and Society* 20 (1). https://doi.org/10.5751/ES-07380-200152.

Biggs, Reinette, Garry D. Peterson, and Juan C. Rocha. 2018. "The Regime Shifts Database: A Framework for Analyzing Regime Shifts in Social-Ecological Systems." *Ecology and Society* 23 (3): art9. https://doi.org/10.5751/ES-10264-230309.

Buitenwerf, R., W. J. Bond, N. Stevens, and W. S W Trollope. 2012. "Increased Tree Densities in South African Savannas: >50 Years of Data Suggests CO 2 as a Driver." *Global Change Biology* 18 (2): 675–84. https://doi.org/10.1111/j.1365-2486.2011.02561.x.

Case, Madelon F., and A. Carla Staver. 2017. "Fire Prevents Woody Encroachment Only at Higher-than-Historical Frequencies in a South African Savanna." *Journal of Applied Ecology* 54 (3): 955–62. https://doi.org/10.1111/1365-2664.12805.

Cerutti, Paolo Omar, Phosiso Sola, Audrey Chenevoy, Miyuki Iiyama, Jummai Yila, Wen Zhou, Houria Djoudi, et al. 2015. "The Socioeconomic and Environmental Impacts of Wood Energy Value Chains in Sub-Saharan Africa: A Systematic Map Protocol." *Environmental Evidence* 4 (1): 12. https://doi.org/10.1186/s13750-015-0038-3.

Crépin, Anne-Sophie, Reinette Biggs, Stephen Polasky, Max Troell, and Aart de Zeeuw. 2012. "Regime Shifts and Management." *Ecological Economics* 84: 15–22. https://doi.org/10.1016/j.ecolecon.2012.09.003.

D'Odorico, Paolo, Gregory S. Okin, and Brandon T. Bestelmeyer. 2012. "A Synthetic Review of Feedbacks and Drivers of Shrub Encroachment in Arid Grasslands." *Ecohydrology* 5 (October 2011): 520–30. https://doi.org/10.1002/eco.259.

Egeru, A S. 2014. "Energy Sources, Part B: Economics, Planning, and Policy Rural

Households' Fuelwood Demand Determinants In Dryland Areas of Eastern Uganda Rural Households' Fuelwood Demand Determinants In Dryland Areas of Eastern Uganda." *Economics, Planning, and Policy* 9 (1): 39–45. https://doi.org/10.1080/15567241003716688.

Ellis, J.E., and D.M. Swift. 1988. "Stability of African Pastoral Ecosystems: Alternate Paradigms and Implications for Development." *Rangeland Ecology & Management / Journal of Range Management Archives* 41 (6): 450–59. https://journals.uair.arizona.edu/index.php/jrm/article/view/8307.

Folke, Carl, Steve Carpenter, Brian Walker, Marten Scheffer, Thomas Elmqvist, Lance Gunderson, and C.S. Holling. 2004. "Regime Shifts, Resilience, and Biodiversity in Ecosystem Management." *Annual Review of Ecology, Evolution, and Systematics* 35 (1): 557–81. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711.

Hamann, Maike, Reinette Biggs, and Belinda Reyers. 2015. "Mapping Social–ecological Systems: Identifying 'Green-Loop' and 'Red-Loop' Dynamics Based on Characteristic Bundles of Ecosystem Service Use." *Global Environmental Change* 34: 218–26. https://doi.org/10.1016/j.gloenvcha.2015.07.008.

Hoffman, M.T. 2014. "Changing Patterns of Rural Land Use and Land Cover in South Africa and Their Implications for Land Reform." *Journal of Southern African Studies* 40 (4): 707–25. https://doi.org/10.1080/03057070.2014.943525.

Millennium Ecosystem Assessment. 2005. "Ecosystems and Human Well-Being: Synthesis." Washington, DC.

Moncrieff, Glenn R., Simon Scheiter, William J. Bond, and Steven I. Higgins. 2014. "Increasing Atmospheric CO2 Overrides the Historical Legacy of Multiple Stable Biome States in Africa." *New Phytologist* 201 (3): 908–15. https://doi.org/10.1111/nph.12551.

Russell, Jennifer M., and David Ward. 2014. "Remote Sensing Provides a Progressive Record of Vegetation Change in Northern KwaZulu-Natal, South Africa, from 1944 to 2005." *International Journal of Remote Sensing* 35 (3): 904–26. https://doi.org/10.1080/01431161.2013.873154.

Sankaran, Mahesh, Niall P Hanan, Robert J Scholes, Jayashree Ratnam, David J Augustine, Brian S Cade, Jacques Gignoux, et al. 2005. "Determinants of Woody Cover in African Savannas." *Nature* 438 (7069): 846–49. https://doi.org/10.1038/nature04070.

Scheffer, M, S Carpenter, J A Foley, C Folke, and B Walker. 2001. "Catastrophic Shifts in Ecosystems." *Nature* 413 (6856): 591–96. https://doi.org/10.1038/35098000.

Skowno, Andrew L., Mark W. Thompson, Jens Hiestermann, Brad Ripley, Adam G. West, and William J. Bond. 2017. "Woodland Expansion in South African Grassy Biomes Based on Satellite Observations (1990–2013): General Patterns and Potential Drivers." *Global Change Biology* 23 (6): 2358–69. https://doi.org/10.1111/gcb.13529.

Smit, G.N N. 2004. "An Approach to Tree Thinning to Structure Southern African Savannas for Long-Term Restoration from Bush Encroachment." *Journal of Environmental Management* 71 (2): 179–91. https://doi.org/10.1016/j.jenvman.2004.02.005.

Smit, Izak P.J., Gregory P. Asner, Navashni Govender, Nicholas R. Vaughn, and Brian W. van Wilgen. 2016. "An Examination of the Potential Efficacy of High-Intensity Fires for Reversing Woody Encroachment in Savannas." *Journal of Applied Ecology* 53 (5): 1623–

33. https://doi.org/10.1111/1365-2664.12738.

Stevens, Nicola, B. F. N. Erasmus, S. Archibald, and W. J. Bond. 2016. "Woody Encroachment over 70 Years in South African Savannahs: Overgrazing, Global Change or Extinction Aftershock?" *Philosophical Transactions of the Royal Society B: Biological Sciences* 371 (1703): 20150437. https://doi.org/10.1098/rstb.2015.0437.

Venter, Z. S., M. D. Cramer, and H.-J. Hawkins. 2018. "Drivers of Woody Plant Encroachment over Africa." *Nature Communications* 9 (1): 2272. https://doi.org/10.1038/s41467-018-04616-8.

Vermeulen, S. J., B. M. Campbell, and J. J. Mangono. 2000. "Shifting Patterns of Fuel and Wood Use by Households in Rural Zimbabwe." *Energy & Environment* 11 (3): 233–54. https://doi.org/10.1260/0958305001500112.

Wehner, Joachim. 2000. "Development Strategies in Post-Apartheid South Africa." *Africa Spectrum* 35 (2): 183–92. https://doi.org/10.1080/02589349508705014.

Wigley, B. J., W. J. Bond, and M. T. Hoffman. 2009. "Bush Encroachment under Three Contrasting Land-Use Practices in a Mesic South African Savanna." *African Journal of Ecology* 47: 62–70. https://doi.org/10.1111/j.1365-2028.2008.01051.x.

Wigley, Benjamin J., William J. Bond, and M. Timm Hoffman. 2010. "Thicket Expansion in a South African Savanna under Divergent Land Use: Local vs. Global Drivers?" *Global Change Biology* 16 (3): 964–76. https://doi.org/10.1111/j.1365-2486.2009.02030.x.

CHAPTER 7: APPENDICES

7.1 CHAPTER 5: QUESTIONNAIRES

I am a PhD student at the University of Stellenbosch involved in research that seeks to better understand local land users' perceptions to bush encroachment and how it impacts them. This research will help us understand how local land users interact with their changing environment and services they derive from it, as this often directs land use management. Interviewees will be community members, private and state reserve managers in Hluhluwe – this will contribute towards our understanding how social and ecological systems can be managed more effectively for future sustainability. As such, your participation in this research is greatly appreciated. The interviews will take part in February and March 2018 and will be on average 45-60 minutes long. Participation in this study is entirely voluntary and this study is informed by a strict ethical protocol.

Context:

Interview no.	
Date	
Site	
Data capturer	
Date of capture	

Part A: Biographic details

Land use type	L.C	C.F	G.R
Age			
F/M			
Race:			
Owner	Renting	Rent Free	
No. of people in household			
Where are you from?			

Education	
Some PS	
Completed PS	
Some HS	
Matriculated	
Higher Education	
Post Graduate	

Notes

1. Number of wage earners in household______

2. Job Types of wage earners

____

3. Number of pension holders_____ 4. Number of other grant holders_____

5. Are there family members who live in the city during the week or certain months who contribute to the household income?__________

6. How long have you lived in this location_________

Section B

Livestock ownership

7. Do you keep any livestock? [Yes] [No]

8. What type of livestock? [cattle] [sheep] [goats] [other]

9. How many units? Cattle___ Sheep____Goats____Other____

10. What is the main reason for keeping livestock?

____

11. Has this changed over the past 20 years? [Yes] [No]

12. How has it changed?

____

13. When did you make those changes

why did you make those changes?

14. Has your ability to take care of your livestock changed over time? [Yes] [No]

15. How?

____

16. Has your sense of personal and household security changed over time? [Yes] [No]

____

17. Has your ability to feed and manage your household changed over time? [Yes] [No]

18. Can you have examples to share with me?

____

Section C

Knowledge and Perceptions of the landscape

19. How has the number of trees changed in the landscape over the last 20 years?__________

How? [Increased] [Decreased] [Remained Constant]

20. Do you think it's a problem? [Yes] [No] [Not sure]

21. Do you have trees on your property? [Yes] [No] [Not sure]

22. Were these trees planted? [Yes] [No] [Not sure]

23. How many trees do you have on the property [0-5] [6-10] [11-20] [20-40] [>40] on your property?

24. Are trees spreading on your property? [Yes] [No] [Not sure]

25. Are trees spreading in the area? [Yes] [No] [Not sure]

26. How has the spreading of the trees impacted you and your livelihood?

27. Please explain____

____

28. Has the use of grass for grazing for your livestock changed over the years? [Yes] [No] [Not sure]

29. If so, how?

____

30. Has the use of water for you or your livestock changed over the years? [Yes] [No] [Not sure]

____

31. Do you have piped water on the property [Yes] [No]

____

32. Do you collect from elsewhere? [Yes] [No]

33. Do you plant any crops on your property? [Yes] [No]

34. Why?____

35. Has anything changed in how you use your property? [Yes] [No]

36. How?____

37. Has anything else changed in how you use the landscape? [Yes] [No]

38. How?____

Section D

Uses of the trees and natural resources

39. Does your household harvest trees or any other resources? [Yes] [No] [Not Sure]

40. What do you harvest these resources for?

Use	Own Use?	Quantity/month	Sale?	Quantity/month	Collection Point
Fuelwood					
Fodder					
Building Material					
Furniture					
Food					
Medicine					
Utensils					
Mats/ivovo					
Decorations					
Thatch					
Other					

41. Has this changed over time?

42. How?____

43. Do trees also provide other non-direct use benefits? [Yes] [No]

44. What?

____

45. Does it cost you anything to harvest the trees? [Yes] [No]

46. How much (money &/or time)?____

47. Do you sell the wood? [Yes] [No] [Not Sure]

____

48. How many hours a week do you harvest?____________________________________

49. Do you employ someone to help you? [Yes] [No]

50. How many people?____

51. Has your use of trees [Increased] [Remained Constant] [Decreased] over the last 15-20?

52. Why?

____

53. Do you do anything to try and counter the change?

____

54. What do you think is the main cause of the increased trees in the landscape and why?

____

55. What management strategy do you apply on the property?

____

56. Do you have any further input or bush encroachment impacts not discussed in the interview you would like to add?

____

For game reserve managers

Part A: Biographic details

Land use type	
Age	
F/M	
Race:	
Education level	
How long have you worked here?	

Part B: Knowledge and Perceptions of the landscape

1. Has there been major changes in the landscape that you've noticed? [Yes] [No]
2. Are there more trees in the landscape? [Yes] [No] [Not sure]
3. Do you think it's a problem? [Yes] [No] [Not sure]
4. ____

5. Are they [Very Common] [Common] [Moderate] [Scarce] [Very Scarce] on your reserve?
6. Are trees spreading on your reserve? [Yes] [No]
7. Are trees spreading in the general area? [Yes] [No]
8. Are the trees [Beneficial] [Harmful] [No Impact] for the business and the way you manage the reserve?
9. Please explain____

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    ____

10. Has the use of grass for grazing and water for your game changed over the years? [Yes] [No]
11. If so, how?

    ____

    ____

12. Do you clear-fell? [Yes] [No]
13. Does it cost you anything to clear the trees? [Yes] [No]
14. How much (money &/or time)?____
15. If you sell the wood, where do you sell it?

    ____

    ____

16. How many hours a week do you harvest?____________________________________
17. Do you employ someone to help you? [Yes] [No]
18. How many people?____
19. Has the reserve's use of trees [Increased] [Remained Constant] [Decreased] over the last 10-20?
20. Why?

    ____

    ____

21. Do you have any other bush management strategies?

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    ____

22. What does that cost in both time and money?

____

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23. How often do you have to do this? ___________________________________

24. What do you think is the main cause of the increased trees in the landscape?

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    ____

25. Why do you think so?

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    ____

26. What management strategy do you apply on the property?

    ____

    ____

27. Has it been a successful strategy or do you think it would be beneficial to do something else?

    ____

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28. Do you have any further input or bush encroachment impacts not discussed in the interview you would like to add?____

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