Patterns and drivers of long term spatio-temporal change in a rural savanna landscape

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Declaration

I declare this thesis to be my own, unaided work, unless otherwise noted within the text. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any other degree or examination in any other university.

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Abstract

Ecosystem services provide a vital lifeline to millions of people living in rural areas. The poorest people in these areas depend upon the natural resource base in their surroundings to provide these services. With growing populations in rural areas of South Africa, the natural resource base is under considerable pressure; however, uncovering the dynamics of vegetation in these systems has proven difficult. While much attention has been given to savanna ecology, long term studies on the patterns and drivers of woody biomass are few. We used 65 years of aerial imagery (from 1944 to 2009) over 31 953 ha of rural savanna in a communal rangeland in South Africa to determine the abundance of woody canopy cover. This data were captured at hectare resolution, giving a fine enough level of detail for local level analysis. We also captured data for five potential drivers for change at this resolution, in order to analyse these drivers for their relative importance in determining woody canopy cover throughout the study period. Surprisingly, while individual sites showed varied trends in the amounts of woody canopy cover through time, when pooled across all sites the total woody canopy cover increased over the 65 year period. Disturbance gradients were found around some of the villages, but only in 2009, suggesting that the drivers of disturbance gradients in these systems may have only operated sufficiently to produce disturbance gradients in recent years. A hot spot analysis (hot spots indicate cells that have similarly high values beyond what would be expected in a random distribution, with cold spots indicating the inverse) revealed an increase in both hot and cold spots through time, but with a low persistence of both through time. High canopy cover cells are presumed to be the result of bush encroachment, while low canopy cover cells are presumed to be the result of harvesting of trees for fuelwood or clearing for fields. The low persistence of hot and cold spots points to a system in continual change, with patches of hot and cold spots appearing and disappearing, and therefore drivers of change operating in short periods of time. MAP (Mean Annual Precipitation), and not an anthropogenic driver, was found to be the most important driver for woody canopy cover throughout the study period, with MAP up to 670 mm having a predictable pattern of hot and cold spots through time. Higher MAP was shown to have a non-linear and unpredictable pattern of hot and cold spots through time, indicating that low precipitation may produce a system where woody canopy cover is less influenced by other drivers and is more stable when acted upon by other drivers. This research demonstrates the value of a long term dataset, and the applicability of our methods for monitoring woody canopy cover. As such, it may well serve as a baseline for woody canopy cover in communal savanna rangeland systems, with the methodology employed here suitable for an early warning detection system for sudden changes in the woody canopy cover.

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List of Abbreviations

APM	Automatic Point Measurement
BBR	Bushbuckridge
CSR	Complete Spatial Randomness
DEM	Digital Elevation Model
DLT	Direct Linear Transform
GCP	ground control point
K	Kappa statistic
MAP	Mean Annual Precipitation
NGI	National Geo-spatial Information
NTFP	Non-Timber Forest Products
OBIA	Object Based Image Analysis
SUCSES	Sustainability in Socio-Ecological Systems
TPI	Topographic Position Index

1. Introduction

1.1 Rationale

Savannas, covering 20% of the world's surface (Scholes & Walker, 1993), provide a multitude of environmental services. Determining their ability to maintain these services is important, since a decline in their ability to do so would have far reaching consequences. Seventy percent of the former *bantustan* areas (areas people were forcibly relocated to, under the former Apartheid government) in South Africa are in the savanna biome (Shackleton et al., 2007a). Bushbuckridge (BBR), Mpumalanga province, South Africa, is one of these former *bantustan* areas and now consists of multiple villages on land where settlements and croplands are embedded in a matrix of communal rangeland, which is the dominant land use (Figure 1.1). The local people make considerable use of natural resources for a variety of products and uses (High & Shackleton, 2000). Due to high unemployment rates (Twine, 2005) and the weakening of regulation by local authorities (Twine *et al.*, 2003; Giannecchini *et al.*, 2007), these common property resource systems (i.e. the communal rangelands) tend towards open access systems (Dovie *et al.*, 2004), which may compromises sustainability. Extraction of woody resources occurs in the form of removal of stems and branches of trees for fuelwood, carving and furniture, leading to a disturbed landscape where species' abundance and diversity may be changed.

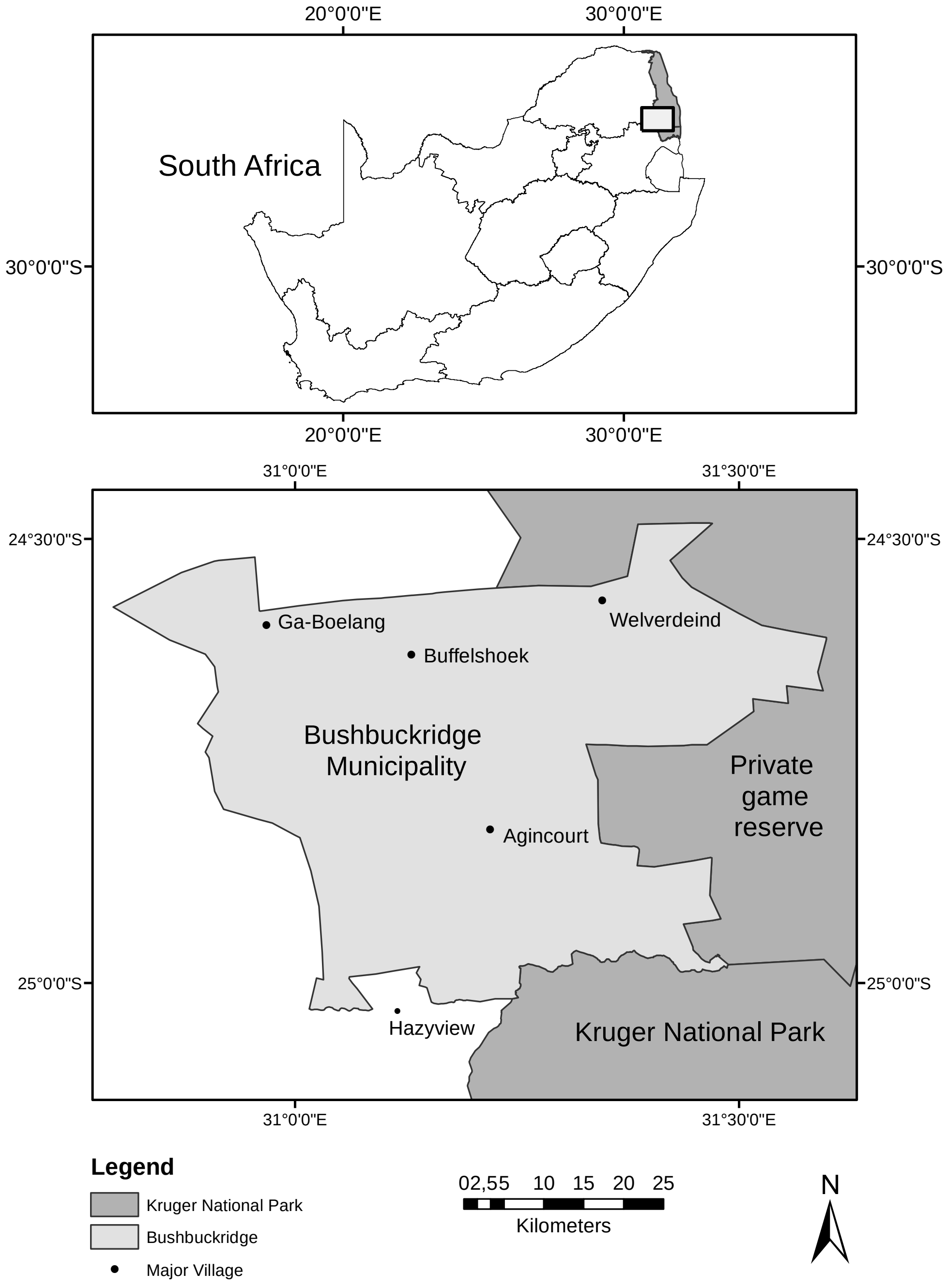

Figure 1.1: The location of Bushbuckridge, Mpumalanga province, South Africa

The extraction rate of woody resources, which impacts the woody canopy cover, is influenced by many factors. Population is important in determining the number of people potentially utilising natural resources in their immediate surroundings. Beginning in the 1960s, millions of black South African’s were forcefully relocated to areas of low agricultural productivity, with limited infrastructure (Platzky & Walker, 1985). The former Gazankulu and Lebowa *bantustans* make up the majority of present day BBR, and this area was subject to this forced relocation to pursue “separate development” (Thornton, 2002). This continued into the 1980’s, where there was an additional influx of Mozambican refugees entering the area, increasing the population size (Gianecchinni *et al.*, 2007). Democratic change 20 years ago was associated with a weakening of traditional authorities and resource governance in BBR and other former homelands (Twine, 2005). In addition to anthropogenic factors, there are other abiotic factors which may be potential drivers or limits of woody plant cover. There is a steep east to west rainfall gradient, with higher human populations in the wetter west, and two distinct underlying geological types (Acocks, 1988). At a finer scale, the topography and the soils are important - especially the catenal sequence of sandy to clayey soils in granitic geological areas (Cronje *et al.*, 2008).

Although previous research has addressed the impact of the extraction of these natural resources from human impacted savannas, most has been done in response to a certain species, type of vegetation class or product derived from these resources. An analysis of the change in density and structure of woody vegetation that is spatially and temporally explicit would uncover trends not visible at smaller scales, provide management with insights into long term trends so as to inform decisions for policy, and provide a baseline for future research into these trends. BBR is a well suited area to perform such a study because it is a large area, consisting of open communal rangeland, interspersed with rural villages. Additionally, data exist (in the form of aerial images) for over 70 years of the entire area, and it is readily available.

The aim of this research is to uncover patterns and trends in woody canopy cover in a human-impacted African savanna landscape, and to analyse them in relation to drivers of woody canopy cover over varying spatial scales and several decades. Special focus is given to anthropogenic drivers, but other biotic and abiotic drivers are also considered.

1.2 Literature review

1.2.1 Savanna woodlands

Savannas, characterised by a co-dominance of trees and grasses, occupy more than one fifth of the world's land surface, and roughly 40% of Africa's land surface (Scholes & Walker, 1993; Riginos *et al.*, 2009). It is the largest biome in South Africa (covering 33% of the land surface), while 77% of it is untransformed, 9% partially transformed, and 14% totally transformed (Thompson *et al.*, 2001). The importance of the savannas cannot be underestimated, as they harbour most of the world's rangelands, mammal diversity and livestock (Riginos, 2009), and millions of people depend on their ecosystem services for their livelihood (Higgins *et al.*, 1999). Savannas are disturbance-driven systems, characterised by an inherently unstable mix of trees and grasses. Even in a state which is undisturbed by humans, savannas show high temporal and spatial heterogeneity (Walker, 1976; Frost, 1996).

Savannas are characterized by the coexistence of trees and grasses, and the physiognomy of savannas is fundamentally distinct form grasslands and forests (Higgins *et al.*,2000); making structure of savannas a function of the ratio between the two. This ratio, and its spatial configuration, is determined by a range of environmental factors. Debate exists over what the main drivers are for this balance in the ratio. Some researchers focus on local scale disturbances, such as variations in fire and rainfall intensity (Higgins *et al.*, 2000), herbivory (Skarpe 1992), rainfall and soil characteristics (Skarpe, 1992; Frost, 1996), fire (Skarpe, 1992; Frost, 1996), human activities (Frost, 1996) and the interplay between rainfall and inter-tree competition (Wiegand *et al.*, 2006). Others look to more global phenomena, such as atmospheric CO_2 changes (Ward, 2010; Buitenwerf *et al.*, 2012).

1.2.2 South African communal rangeland savannas

In South Africa, savannas contain 96% of the wooded land in the country, and 25% of this is communal land (Shackleton *et al.*, 2007a). The communal lands, in this study, refer to rural areas of communal land tenure, and they are in locations that were previously known as *bantustan* areas in South Africa. These *bantustans* were ethnically-based self-governing territories established through forced re-settlement. Since democratic change took place in 19944, governance comes from a mixture of traditional and governmental institutions. Traditional authorities had control over natural resources prior to democracy, but now they are weakening and becoming marginalised, as tension mounts because jurisdiction is unclear (Dovie *et al.*, 2004; Twine, 2005; Giannecchini *et al.*, 2007). These areas remain poverty stricken, and they rely on the natural resource base for most of their energy needs, which acts as a buffer against poverty (Shackleton *et al.*, 2001, Dovie *et al.*, 2002). Although government has rolled out a widespread electrification programme in rural areas in order to address historical inequalities (Eberhard, 1995), 90% of households in BBR still use fuelwood for their cooking energy needs (Madubansi & Shackleton, 2006). Electrification was, and still is, seen by the government as a solution to alleviate the reliance on fuelwood (Dovie *et al.*, 2004). However, many of the newly electrified residences in rural areas do not use the electricity for cooking and heating because they cannot afford the appliances needed and the monthly costs of the electricity (Twine *et al.*, 2003; Twine *et al.*, 2005; Shackleton, 2007b). Additionally, electricity presents a safety risk, and fuel-efficient stoves produced by businesses in urban areas were produced without any consultation with the local people - they have developed their own coping strategies to environmental stressors (Dovie *et al.*, 2004). A study showed that the amount of fuelwood used (mostly for thermal needs) by households in five villages in BBR in the decade following 1992, did not change despite electrification (Madubansi & Shackleton, 2006). The government's free energy allowance was not seen as an alternative energy source, but an additional one and used for powering entertainment devices (Madubansi & Shackleton, 2006).

1.2.3 Drivers on the broadest scale: the roles of geology, soil and rainfall on the distribution of savannas and their types

Tree abundance in savannas is influenced by geology at a broad, regional scale (Goughenour & Ellis, 1993) (see Figure 1.2 for a conceptual framework). The soils found in an area are a product of the parent geology, and South African lowveld savannas predominantly occur on basalt and granite, although a mixture of other geological types is apparent (Acocks, 1988). In terms of vegetation, the structural and textural properties of the soil are important because they determine the amount of water available for plants (Ashman & Puri, 2002). The infertile granite areas tend to have broad-leaved vegetation that employ chemical defense over physical defense, while the basalt areas tend to have a higher clay content which is more suitable for fine-leaved thorny vegetation (Scholes, 1997). At a finer scale, South African savannas are characterised by a vegetation structure driven by the topographic soil structure (catenal position) (Scholes & Walker, 1993) with plant productivity reflected along this catenal soil gradient; a higher plant productivity at the bottomlands moving towards lower productivity in the toplands (Cronje *et al.*, 2008).

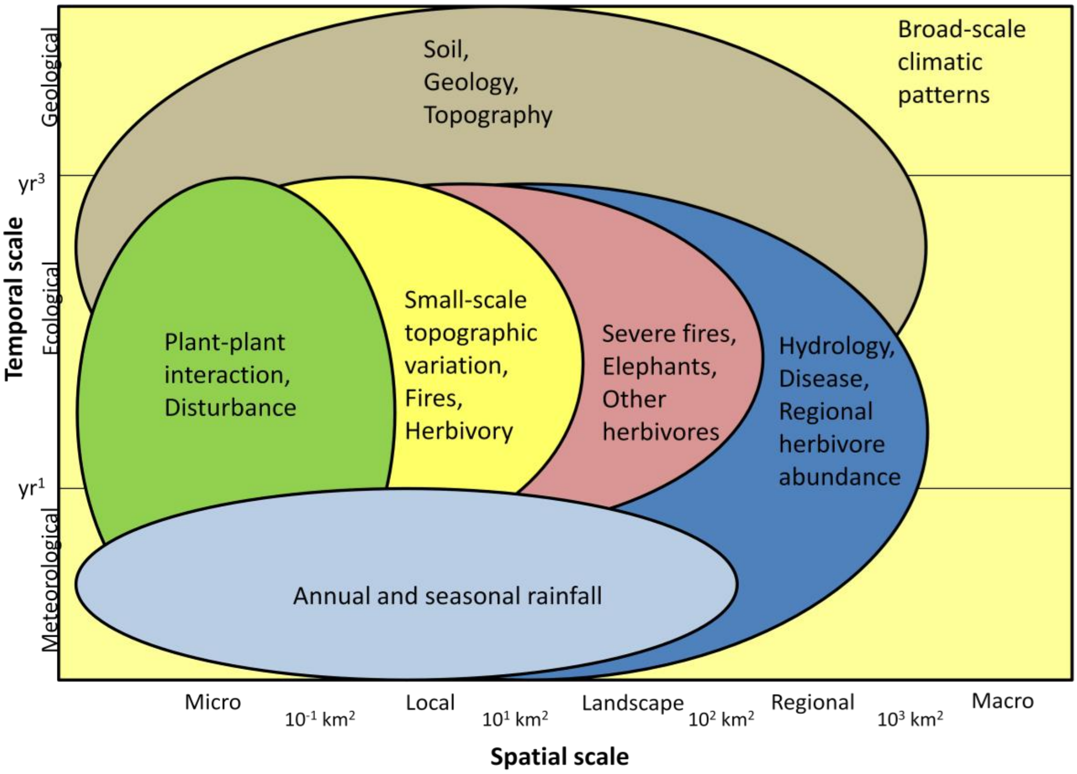

Figure 1.2: A spatio-temporal framework for processes that shape savanna tree density (Gillson, 2004).

Additionally, underlying geology has been found to have a profound impact on catenal-plant sequences in lowveld savannas: plant biomass has been found to have a linear relationship on basalts with lowest biomass on crests increasing linearly towards streams, while on granite substrates plant biomass has been found to be highest on crests, decreasing midslope and then increasing towards streams (Colgan *et al.*, 2012). The soil type of an area in a Savanna influences the tree density (Skarpe, 1992), and the combination of soil type and rainfall (soil moisture) has a marked effect on woody phenology (Shackleton, 1999).

Some argue that water is the chief determinant of woody cover in savannas (Walter, 1971; Walker e*t al.*, 1982; Walker & Noy-Meir, 1982). In lowveld (low altitude) savannas there is a strong relationship between the mean annual rainfall and the species richness (Shackleton, 2000). One recent, large scale, study found that savanna systems receiving less than 650mm of mean annual precipitation (MAP) are stable (MAP controls the upper bound of woody cover and permits grasses to coexist, while other driver such as fire and herbivory interact to limit the woody cover below the MAP controlled upper bound), while systems receiving above 650mm are unstable (MAP is sufficient for woody canopy closure and disturbance are needed for grasses to coexist) (Sankaran *et al.*, 2005).

Rainfall appears to influence the phenology of woody communities in South Africa. Higher rainfall influences the onset and magnitude of leaf emergence (leaf growth initiated earlier) and the onset and emergence of mature leaves (occurring earlier and mature leaves lasting longer) (Shackleton *et al.*, 1999). It also influences the proportion of leafless trees - with a higher proportion at arid localities, than semi-arid localities and the lowest at the moist localities in the dry season (Shackleton *et al.*, 1999).

1.2.4 Broad scale anthropogenic effects; land use types and their influence on lowveld savanna vegetation

Different land use types can have large and obvious effects on vegetation structure and richness. Sala (1995) states that land use change is the driver of the highest magnitude in terms of biodiversity loss. In classical rangeland theory, communal rangeland management is seen as unsustainable and unproductive (Abel, 1993 in Parson *et al.*, 1997). Other research, however, points to the conclusion that it may be otherwise (Parson *et al.*, 1997; Harrison & Shackleton, 1999), possibly due to the resilience and the capacity for adaptation of communal rangelands, and their dynamic and heterogeneous nature (Giannecchini *et al.*, 2007). When comparing communal lands to protected nature reserves, Shackleton (2000) found that communal lands had a lower vegetation structure (in terms of height and cover) with more bare ground, but were not lacking in variety of plant species. In fact, there were significantly more plant species found in the communal lands, and all functional groups were found in the communal lands in that study. Shackleton (2000) points out that these new findings do not mean that nature reserves are not achieving goals (as many of them proclaim maintaining biodiversity is their main goal), but that communal land use does not necessarily lead to a loss of plant species.

Higgins *et al.* (1999) found that toplands and bottomlands respond differently to land management schemes, possibly because toplands are utilised more for harvesting or because toplands are less resilient to human land management. The communal lands have been shown to be resilient (Shackleton, 1993b; Harrison & Shackleton, 1999; Giannecchini *et al.*, 2007) which may be due to the resprouting and coppicing ability of savanna species. This does not undermine the effects of communal land use systems on the species richness and abundance of woody plants, as this resilience may also be due to a lag phase between reduction in abundance and species loss due to loss of large reproductive trees (Higgins *et al.*, 1999; Twine, 2005). Additionally, land use can override the effects of soil type manifest through slope position (Parsons *et al.*, 1997). Communal rangelands are increasingly becoming characterised by short, multi-stemmed trees (Neke, 2002) and future losses of species are thus likely (Higgins *et al.*, 1999).

1.2.5 Anthropogenic effects on lowveld communal savannas

Almost all of the households in the rural lowveld use resources harvested from the communal lands to provide energy in the form of fuelwood (Dovie *et al.*, 2002; Dovie *et al.*, 2004; Kaschula *et al.*, 2005), food (Dovie *et al.*, 2002; Shackleton *et al.*, 2002; Shackleton, 2004), construction materials (Dovie *et al.*, 2002), form of income (High & Shackleton, 2000; Dovie *et al.*, 2002; Shackleton *et al.*, 2002; Shackleton, 2004; Shackleton & Campbell, 2007), medicine (Dovie *et al.*, 2002; Shackleton, 2004) and crafts and other resources (Dovie *et al.*, 2002; Shackleton *et al.*, 2002; Shackleton, 2004). These natural resources are also valued for non-economic purposes, such as cultural uses (Cousins, 1999). This may be under-appreciated - Cocks & Wiersum (2003) found that just over half (in terms of use value) of the natural non timber products harvested in a rural area in the former Ciskei *bantustan* were used for cultural purposes. Grazing is also found in the communal rangelands (Harrison & Shackleton, 1999), and has a notable impact in lowveld savannas because of the amount of land that is uses.

1.2.5.1 Harvesting of natural resources for domestic use

Ninety four percent of households in BBR use fuelwood as their main energy source (Shackleton & Shackleton, 2000) and natural resources are used to produce products that are sold for income, often as an invaluable safety net in times of crisis (Dovie *et al.*, 2002). However, the strength of these products as a safety net has not been quantified and is generally underappreciated (Paumgarten, 2005). While the financial returns are low, they are important in that they diversify the livelihood strategies, especially in poorer households, and may also contribute non-financial benefits (Shackleton & Shackleton, 2004). While there is a drive to electrify rural areas in South Africa, studies in BBR have found that 68% of rural households that are electrified still use fuelwood as their primary energy source for their daily needs, because they cannot afford the electricity (Matsika *et al.*, 2013). Matsika *et al.* (2013) continue that it is ironic that if households were to purchase electricity they would have less funding available for other households necessities such as food, clothing and education, it is thus a financial cost and not an aid as intended. Although, fuelwood collection is time intensive, households would rather spend this time collecting fuelwood than paying for electricity, as income and employment opportunities are limited (Matsika *et al.,* 2013).

Some research has found that due to a shortage in some desirable species local inhabitants have taken to removal of other, less desirable, species in order to fulfil their need for some of the resources, especially fuelwood (Madubansi & Shackleton, 2007). This shows that in some areas certain species are locally extinct, and in many areas they may not be at reproductive numbers for long term sustainability. Matsika *et al.* (2012) found that in a village where there was a reduction in resource abundance, there was a decrease in the diameter of stems harvested and an increase in the harvesting of smaller stem size classes. Since the local people rely on fuelwood so heavily, the high levels of harvesting have led some authors to the conclusion that there is a fuelwood crisis in South Africa (e.g. Dovie *et al.*, 2004). However, there is data that suggest that there are in fact enough resources at a national scale to meet fuelwood demand (Williams & Shackleton, 2001). This would relieve the pressure on the local land, but much of the resources are in state and private land, making them difficult to acquire (Shackleton *et al.*, 2007b). Thus, extraction is spatially heterogeneous, with regard to different land uses in any particular area.

Fuelwood is very important to the livelihoods of rural people in South Africa as it is a dominant source of energy (Kaschula *et al.*, 2005; Giannecchini *et al.*, 2007). The amount consumed has been found to be correlated with the number of women in a household, as they are responsible for the majority of cooking and heating (Dovie, *et al.*, 2004). Fuelwood is also important as it supplies energy for other economic activities (Shackleton *et al.*, 2007a). Villagers in Thorndale village, BBR, have been found to collect fuelwood in headloads (on a person's head), wheelbarrows or in a pickup vehicle (Dovie *et al.*, 2004), thus methods of extraction are varied. There is little difference between the amounts of fuelwood harvested in summer and winter months in that study, primarily because there are more festivities in the summer months, which balance out with the need for more fuel in winter for heat (Dovie *et al.*, 2004).

1.2.5.2 Natural resource harvesting as an income generating strategy

As well as using these goods for themselves, it has been found that many of them are sold in order to diversify livelihood strategies (Dovie *et al.*, 2002) and alleviate poverty, or at a minimum prevent the intensification of poverty (Twine, 2003; Shackleton, 2004; Shackleton *et al.*, 2007a; Cocks *et al.*, 2008). The harvesting of natural resources acts as a buffer against socio-economic shocks, such as job losses, crop failures (Dovie, 2002) and the loss of an income earning husband - in the case of the broom trade especially (Shackleton & Campbell, 2007). High & Shackleton (2000) found that in BBR, on average, 28% of the value of all harvested natural resources harvested by a household were sold, and the remaining 72% was consumed by the household. From 1992 to 2002 there was an increase in the number of households purchasing fuelwood (Madubansi & Shackleton, 2006). The extra income creates a safety net for the poorest households, since there are low barriers of entry to trade, resources are freely available, capital costs are minimal and locals have the skills required (Dovie *et al.*, 2002; Shackleton, 2004; Shackleton *et al.*, 2007a; Shackleton & Campbell, 2007). Poor women and the elderly benefit the most from this income strategy; since their low education levels means they have few other options (Shackleton & Campbell, 2007).

The trade in medicinal plants forms the basis of a multi-million rand “hidden economy” (Dold & Cocks, 2002). It is estimated that 20 000 tonnes of medicinal plant material is traded annually in South Africa (Mander, 1998). The demand for the plant parts used is now greater than ever, and needs to be managed in order to achieve sustainability (Dold & Cocks, 2002). Although the income generated from the sale of natural resources, or goods developed from them, may be crucial to the survival of a household it often, more importantly, comes at a time when the cash flow is vitally needed. Shackleton (2004) found that although earnings from the sale of Marula beer (beer made from the fruit of the Marula tree) constituted only 14% of total annual cash earnings, it came in January - when cash is needed to recover from the festive season, for school fees, books, uniforms and shoes. The trade of non-timber forest products (NTFP) may be overlooked in the formal sector because of the nature of the trade (Dovie *et al.*, 2002). The sale of natural resource items, in some cases, leads to income which is more than local wage rates (Shackleton *et al.*, 2008) and correlates with that of livestock and crop production (Cocks *et al.*, 2008), but the earnings vary from household to household (Shackleton & Campbell, 2007). The monetary value of incomes in a household was found not to have any correlation with the mass of fuelwood consumed by the seller, in one study by Dovie (2004). And, the range of natural resources consumed is more in the wealthier households than poorer ones, although the type of goods different between these two socio-economic groups (Twine *et al.*, 2003).

1.2.5.3 Effects of harvesting on vegetation

The use of natural resources presents itself as a human disturbance to the savanna ecosystem, leading to a significant impact on the vegetation (Twine, 2005). Human disturbances occur simultaneously at different intensities and spatial and temporal scales, and are thus varied (Giannecchini *et al.*, 2007). Harvesting pressure, the methods used and the extent of harvesting vary from place to place because society is heterogeneous (Dovie, 2002). In a study in BBR conducted by Matsika *et al.* (2012), harvesting around two villages was found to have caused a decline in the total wood stock in the communal woodlands, with one of the village’s woodlands having a loss in desirable species, a change in the species diversity of commonly harvested species, and a change in the woodland structure. The authors concluded that the woodlands surrounding that village were degraded, while the absence of such impacts in the other village in the study were due to a lower harvesting pressure because of a lower human population.

Shackleton *et al.* (1994) found that harvesting pressure decreased with distance from the edge of each settlement tested, although not significantly. However, around the four settlements the author found that there was a significant decrease in basal area, woody stem density, height, biomass, seedling density and species richness with increasing disturbance. Other studies similarly found disturbance gradients around rural settlements (Banks *et al.*, 1996; Fisher *et al.*, 2011; Wessels *et al.*, 2013), but they seem to disappear around villages that share easily accessible rangelands, resulting in high levels of resource use (Fisher *et al.*, 2011). Over-harvesting of selected species is one of the main threats to savannas in South Africa (Shackleton *et al.*, 2007a), and is driven by market demand (Dovie, 2002). Unsustainable fuelwood harvesting is a threat not only to the resources base, but also to rural livelihoods and the ecology of an area (Shackleton *et al.*, 2007a).

Increasing disturbance appears to affect the majority of woody species negatively, but some non-ruderal species have been found to increase in abundance under high disturbance, while others have become locally extinct (Shackleton, 1994). Higgins (1992) found that mean stem height generally decreases with an increase in proximity to villages. Although selective harvesting of favoured species alters the community species composition and structure, the regenerative potential of lowveld savannas appears to be strong, in that seedling densities have been found to be high, vigorous coppicing was evident and most species still persist under sustained harvesting pressure (Shackleton, 1994).

Coppicing is one of the ways in which a woody plant can survive a disturbance. Factors involved in the plants ability to coppice after a human disturbance are age, the type and severity of the disturbance, the plant size, stump height and percentage of the stand removed (Luoga *et al.*, 2004; Guerro-Campo *et al.*, 2005). Many woody plants coppice and persist *in situ* after the disturbance (Bond & Midgley, 2001), and there is a continuum of responses to a disturbance (Figure 1.3). However, Twine (2005) argues that there is little data on the resilience of coppicing stems that are continually harvested for prolonged periods of time, and that coppicing can be expected to decline in many species harvested because people continually chop lower down to maximise yield. Topland resources are used more heavily than bottomland resources, both by humans (Higgins *et al.*, 1999) and by foraging cattle and goats (Davies, 1993), leading to differences in the composition of woody plant communities. Intense utilisation can lead to a switch in the vegetation state that is outside of the topographic continuum - without utilisation topographic position accounts for much variance in structure and composition of woody plant communities in the savanna lowveld (Higgins et al., 1999).

Increased harvesting pressure on savanna species can lead to changes in tree morphology and thus the vegetation physiognomy. The cutting of live stems of trees, for reasons discussed below, is leading to a change in the vegetation landscape in BBR. There is now a lack of large mature stems and an increase in smaller diameter classes of stems. (Liston 1993, Shackleton 1993a) This has led to an increasing number of adult trees, which are coppicing after being harvested, to being functional juveniles in the sense that they are non-producers of seeds (Twine, 2005).

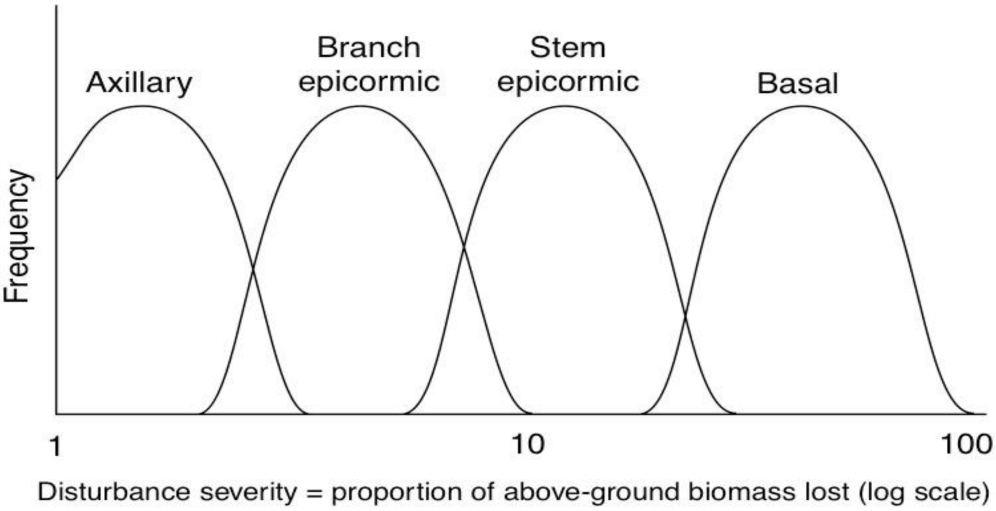

Figure 1.3: The sprouting response depends upon the disturbance severity. Source: Bond & Midgley (2001)

1.2.5.4 Effects of grazing in communal lands on vegetation

Grazing, which is present in the communal lands, is also a form disturbance to the savanna ecosystem. BBR is typically characterised as over-grazed, but this idea is being challenged (Giannecchini *et al.*, 2007). Between the 1960s and 1980s grazing would occur close to settlements, but since the 1990s grazing has occurred further away from settlements due to poor availability of grazing land. Prolonged heavy grazing gives woody plant species a comparative advantage over herbaceous plant species (Otuoma *et al.*, 2009). Harrison & Shackleton (1999), however, found that communal grazing lands are extremely resilient, and in a heavily grazed area rapid changes in species composition and diversity in the herbaceous layer occurred in less than 10 years after grazing was halted. Parsons *et al.* (1997) found that the stocking rate of cattle was the primary correlate with the change in composition of the herbaceous layer occurring under the communal grazing land use type, and not animal type or land use. They did concede, however, that the communal grazing land use type did have a suite of other variables impacting upon the land.

1.2.5.5 Socio-economic and socio-political systems and their impact on lowveld savannas

In these human impacted lowveld savanna ecosystems, socio-economic factors are a critically important component of the variables that influence vegetation change. Conversely, changes in vegetation are important to the people that live in the area because they directly affect the people who rely on the lands natural resource base. This leads to a feedback loop (Figure 1.4). The net effect is that socio-economic change leads to a change in the way resources are harvested – which in the case of African communal savanna rangelands leads to an increase in the intensity of localised harvesting resources and an increase in the volume of resources harvested (Twine, 2005), however it may also work to decrease the volume of resources harvested.

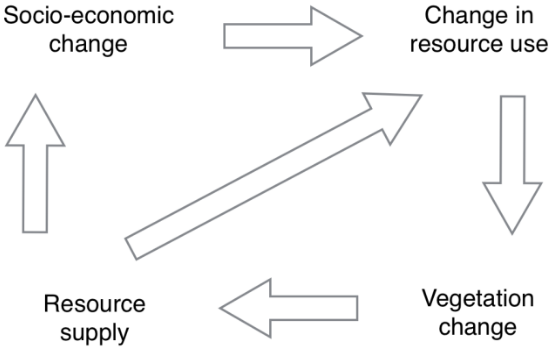

Figure 1.4: Feedback loop between the vegetation change, resource use and socio-economic factors. Adapted from: Twine (2005)

Historically, access to communal land and resources in South Africa were controlled by chiefs and their headmen. During apartheid and colonial times these authorities became bureaucratised, but maintained their function (Thornton as summarized by Twine, 2005, p.94). The chiefs were given a budget for “police” to enforce a set of laws and permits that regulated the harvesting of resources, especially trees. Although flawed, this system moderated the impact on the resource base by humans, especially for certain, key tree species (Twine, 2005). This system is supposed to still be in place, but there is a strong sense of the weakening and marginalisation of these authorities (Twine *et al.*, 2003, Twine, 2005; Giannecchini *et al.*, 2007) and the governance is now unclear as tensions emerge between traditional authorities and newly formed democratic institutions (Dovie *et al.*, 2004). Since the 1994 democratic elections this has become especially evident, and in addition there is now less policing due to government budget cuts and a diminishing respect for traditional authorities by the youth. The local government is not sufficient in managing the natural resources, and this is leading to the development of an institutional vacuum (Twine, 2005).

Due to these factors, certain laws and taboos, which are supposed to be enforced by the traditional authority, are now being increasingly ignored. This is seen firstly in the cutting of live wood for trees, which is supposed to be banned, but is practiced openly today (Dovie, *et al.*, 2004; Twine, 2005; Giannecchini *et al.*, 2007) and secondly in the trading and commercialisation of *Marula* products, particularly beer (Shackleton, 2004). Outsiders are increasingly harvesting in the areas in villages because of the changes in institutional control, especially since the 1994 democratic freedom (Twine, 2005: Giannecchini *et al.*, 2007; Grainger, 2009) and because of an increase in unemployment (Twine, 2005).

Although many authors acknowledge the link between local population size and the demand for natural resources (e.g. Cunningham, 1997; Reyers, 2004; Giannecchini *et al.*, 2007), it is often assumed that the relative wealth of a household relates to their use of natural products, in that lower income households utilise natural resources more. Poorer rural provinces (Statistics SA, 2001), and poorer communities (Twine *et al.*, 2003) rely more heavily on natural resources, but within those communities wealthier household often consume resources more extensively (Paumgarten & Shackleton, 2009). The poorer households rely on “essential” indigenous resources, while the richer households consume more “luxury” indigenous resources (Twine *et al.*, 2003).

1.2.5.6 Increase in human population

An increase in human population will have an effect on the scale of any anthropogenic disturbances in a communal savanna landscape. From the 1960s to 1980s, millions of black South Africans were forcefully relocated to areas of low agricultural productivity, with limited infrastructure (Platzky & Walker, 1985). This was the formation of the *bantustans*, areas where black people were supposed to pursue “separate development” through being self-governing, but these areas had poor infrastructure and were often geographically isolated (Aliber, 2003). BBR was one such area to where people were forcefully relocated. In the 1980s there was an influx of Mozambican refugees into BBR, which caused the population to increase. Although these peoples were of the same ethnic group, and thus became naturalised residents, they have differences in livelihood trends, and are more vulnerable to shocks than their South African counterparts due to the fact that they have less capital (Giannecchini *et al.*, 2007). Clearly, as Hunter *et al.* (2007) points out, there is not enough research on the association between natural resource use in rural areas of Africa and demographic dynamics.

1.3 Aim, objectives and hypotheses

The aim of this research was to further knowledge on human-impacted African savanna landscapes by improving the understanding of impacts upon woody vegetation in the long term (65 years), as these are manifested through patterns and trends in woody canopy cover. Anthropogenic drivers were deemed a key factor in this study; but other biotic and abiotic variables were also considered important factors.

Objectives in this study were to:

1. Uncover if temporal trends in woody canopy cover exist over a large spatial extent over a 65 year time period, using a fine scale of analysis, and investigate anthropogenic influences on woody canopy cover.

    How does woody canopy cover vary through time spatially?

    Is there a relationship between the village area and the abundance and distribution of woody canopy?

    Has the distribution of woody canopy in the landscape become more heterogeneous over the study period?

2. Determine the most important driver, from a set of drivers, for woody canopy cover at each point in time in the study (1944, 1974 and 2009), and throughout the entire study period.

    Which drivers were the most important determinants of woody canopy cover over the study period?

    Are anthropogenic drivers consistent in terms of their importance throughout the study period?

    Are the effects of drivers uniform across their respective spectrum of values (in the case of MAP: the spectrum of values would be low rainfall measurements through to high rainfall measurements)?

1.4 Structure of thesis

Chapters 2 and 3 have been written in a format that allows for submission to scientific journals. Therefore, overlap may occur between these two chapters in order to allow for them to be free standing articles. In certain sections, repetition is unavoidable, such as the methodology.

Chapter 1 is a general introduction to the study, including an overarching literature review, and includes aims, objectives and hypotheses that are investigated in the subsequent chapters. Chapter 2 addresses describing the woody canopy cover spatially over the 65 year period. It deals with how the landscape has changed, if it has become more homogenized, and investigates the relationship between woody canopy cover and the total areas of the villages. Chapter 3 ascertains which drivers, from a predetermined set (selected because they are seen as potentially important), are the most important in determining woody canopy cover. This is done at each of the time periods chosen in this study (1944, 1974 and 2009), and over the whole 65 years. Chapter 4 serves as a synthesis of the finding of chapters 2 and 3, and discusses the findings as a coherent whole, and recommendations drawn from these two chapters are also given.

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2. Patterns of long term spatio-temporal woody vegetation cover in a South African communal rangeland savanna landscape

2.1 Abstract

Communal savanna rangelands in South Africa supply vital natural resources to millions of people. Foremost among their needs is fuel, and this is supplied as woody biomass. Given the turbulent history of many of these areas, extraction of woody biomass has not occurred in a constant or predictable manner. The extraction rate is reflected in the changes in woody canopy cover. In order to understand how the current state of the woody canopy cover developed, which is important for sustainability, historical trends and patterns of woody canopy cover abundance need to be ascertained. Aerial imagery of 31 953 ha, spanning 65 years (from 1944 to 2009), was used to ascertain the patterns of woody canopy cover in a communal savanna rangeland. The results were aggregated into hectare cells, providing a fine enough resolution for local level analysis. While total woody canopy cover across all sites increased drastically throughout the study period, individual sites displayed varied trends in growth and decline of woody canopy cover. A disturbance gradient is present and is visible as lower woody canopy cover surrounding villages up to 1000 m, but again this is village specific, and only present in the latest (2009) data. This signifies that the drivers, specifically harvesting of woody plants, may have only operated recently, or with an intensity that has led to a discernible impact, to create a disturbance gradient. A hot spot analysis, that analysed the relationship between hectare cells of canopy cover, revealed that hot spots (clusters of high canopy cover) and cold spots (clusters of low canopy cover) have increased, both in size and number, throughout the study period. Hot spots indicate cells that have similarly high values beyond what would be expected in a random distribution, with cold spots the inverse. This has led to a landscape which is locally homogenized, but at a broader scale has a higher degree of heterogeneity. Hot spots are presumed to be the result of bush encroachment, while cold spots are presumed to be the result of harvesting of trees for fuelwood or clearing for fields. This landscape is highly dynamic, as seen in the low persistence of hot and cold spots of woody canopy cover through the study period. These results may serve as a baseline for assessing possible trends in woody canopy cover in the area. While we found that there is high variability in the woody canopy cover spatially through time, monitoring whether a trend develops could serve as a valuable management tool.

2.2 Introduction

The importance of savannas cannot be underestimated, as they harbour most of the world's rangelands, mammal diversity and livestock (Riginos, 2009). Roughly 50% of the African continent, and one third of South Africa, is savanna (Shackleton & Scholes, 2010). The South African communal savannas are under high demand for natural resources due to large populations depending on them for a variety of farming and household activities. In fact, over 90% of households in savannas rely on fuelwood as their main energy source, despite the availability of electricity (Madubansi & Shackleton, 2007). With savannas being home to 9.2 million people in South Africa alone (Shackleton, 2000), a significant proportion of the population depends on their ecosystem services for their livelihood (Higgins *et al.*, 1999).

In the former *bantustan* areas in South Africa (self-governing areas where the millions of black people were moved to a specific 13% of the country's land), of which 70% are in savannas (Shackleton *et al.*, 2007b), extraction of natural resources is influenced by many factors. In the past two decades there has been a major shift in political systems in the country, which has accelerated extraction and previously taboo practices, such as cutting of living tree stems and extraction by non-residents with vehicles (Twine, 2005). Additionally, much of the land has changed in use throughout the five decades prior to the political shift, and especially since. Over the past several decades, the population has increased substantially. This is mainly due to the formation of the *bantustans,* which had poor infrastructure and low agricultural productivity, to pursue "separate development" (Aliber, 2003). Additionally, in the 1980s there was a steep increase in Mozambican refugees entering the area, increasing the population at that time (Gianecchinni *et al.,* 2007).

Savannas are disturbance-driven ecosystems, comprising unstable combinations of trees and grasses (Scholes & Walker, 1993). The use of natural resources presents itself as a human disturbance to the savanna ecosystem, leading to a significant impact on the vegetation (Twine, 2005). Human disturbances occur simultaneously at different intensities and spatial and temporal scales, (Giannecchini *et al.*, 2007). Harvesting pressure, the methods used and the extent of harvesting vary from place to place because society is heterogeneous in terms of their settlement density, extraction patterns and harvesting preferences (Dovie, 2002).

In the South African communal savannas, their granitic landscapes show a clear catenal soil sequence, with broad-leaved savanna species occurring on the nutrient poor, upper mid-slopes and toplands, and fine-leaved savanna species occurring on the nutrient rich lower mid-slopes and bottomlands (Scholes, 1997).

Matsika *et al.* (2012) reported a decline in the woodlands around two villages in Bushbuckridge, Mpumalanga; with one village becoming degraded and no longer able to meet fuelwood demand. Other studies have found disturbance gradients around villages due to harvesting pressure (Shackleton *et al.*, 1994; Banks *et al.*, 1996; Fisher *et al.*, 2011; Wessels *et al.*, 2013), with Fisher *et al.* (2011) finding a disappearance of disturbance gradients and a homogenisation of the vegetation structure under extreme harvesting pressure. This disturbance in the vegetation structure may lead to a degradation in the woody resources, and indeed Banks *et al.* (1996) predicted a degradation of resources around two villages in BBR, and Matsika *et al.* (2012) found that while the vegetation had become degraded by the predicted date, the projected complete denudation had not occurred. This shows their resilience to anthropogenic disturbance, but disturbances may still occur at a local level, and the patterns of those disturbances aren't well documented. Savannas are heterogeneous systems (Rogers, 2003), and thus patterns in vegetation structure change through time may reflect the processes and drivers of vegetation dynamics. Indeed, as noted by Levick & Rogers (2011), insight may be gained into the processes underlying vegetation dynamics by analysing the spatio-temporal context of vegetation dynamics.

This study focused on the patterns of woody canopy cover that formed over the study period, addressing the spatial and temporal context of these patterns. It was undertaken to ultimately create a platform for analysis of woody canopy cover and change in communal rangeland savanna landscapes. Given the turbulent history of savannas in the former homelands in South Africa, we expect that in the past there has been an overall decline in woody vegetation, with a series of abnormally rapid, and often non-linear, trends in woody vegetation abundance. These changes may be scale dependent, and occur as a function of distance from village. Additionally, we hypothesise a difference in patterns of woody change between the northern and the southern villages in the study site, with the northern villages having a greater impact on the surrounding natural resources, due to the northern villages tending to be larger and closer to major road systems. This distinction is interesting because it will give insight into the utilization of woody resources in terms of access to other resources, via transport routes and infrastructure. Finally, this research investigated how any observed changes in woody canopy cover occurred, which may be due to an expansion in canopy cover, or a decline and the subsequent emergence of patches of woody canopy cover. In order to understand the local spatial variability of woody canopy cover, a hot spot analysis was performed to produce maps highlighting areas of high and low abundance of woody canopy cover.

2.3 Methods

A communal rangeland in South Africa was chosen as the study site, and 19 sites selected to include villages. Aerial images were prepared for analysis and tree canopies were delineated via object based image analysis (OBIA). An accuracy assessment was conducted, and sites deemed accurate in terms of tree canopy delineation were divided into hectare cells. Data in relation to woody canopy cover and village distance were calculated for each cell. These data were used to perform analysis on how the woody canopy cover is spatially represented through time; how it occurred in relation to the distance to the closest village; how the northern study sites compare to those in the south of the study site; and if the woody canopy cover persists through time as opposed to decreasing and emerging in patches.

2.3.1 Study area

This study was conducted in Bushbuckridge (BBR) Mpumalanga Province, South Africa . Nineteen sites were selected, four based on prominent local villages and towns and the area surrounding them (Thorndale, Athol, and Acornhoek) in the northern half of BBR municipality, and fifteen based on the SUCSES (Sustainability in Socio-Ecological Systems) study area in the southern half of BBR municipality (Figure 2.1). An accuracy assessment (chapter 2.3.5) found that only seven of the nineteen sites were suitable for analysis, and Figure 2.1 reflects the remaining seven sites included in the study. SUCSES is a study being undertaken in order to ascertain the interactions between humans and the environment, and the ecological consequences thereof. The reason our study sites were chosen to overlap with the SUCSES sites is so that parallels may be drawn between the two studies, which may create potential for future research. The study sites were selected around villages because anthropogenic factors are crucial to this study.

BBR is now a single municipality, following democratic change in 1994, but under the former *Apartheid* dispensation, it comprised the *bantustan* districts of Mapulaneng (Lebowa) and Mahla (Gazankulu). There is a distinct east to west gradient in climate, topography and former political boundaries. This has led to distinct land-use zones. The mean annual rainfall in the west is 1200mm and in the drier east it is 550mm. The mean annual temperature is 22° Celsius. The topography of the area is generally flat and undulating, except close to the Drakensberg escarpment in the west, and it has underlying granodiorite and potassic granites. The soils consist of sandy lithosols, but deeper duplex soils are more common towards the base of the catena and close to the Drakensberg escarpment in the west, where deep, apedal soils are present The vegetation is characterised by Lowveld Sour bushveld in the wetter west, which gradually gives way to Lowveld bushveld in the East (Acocks, 1988).

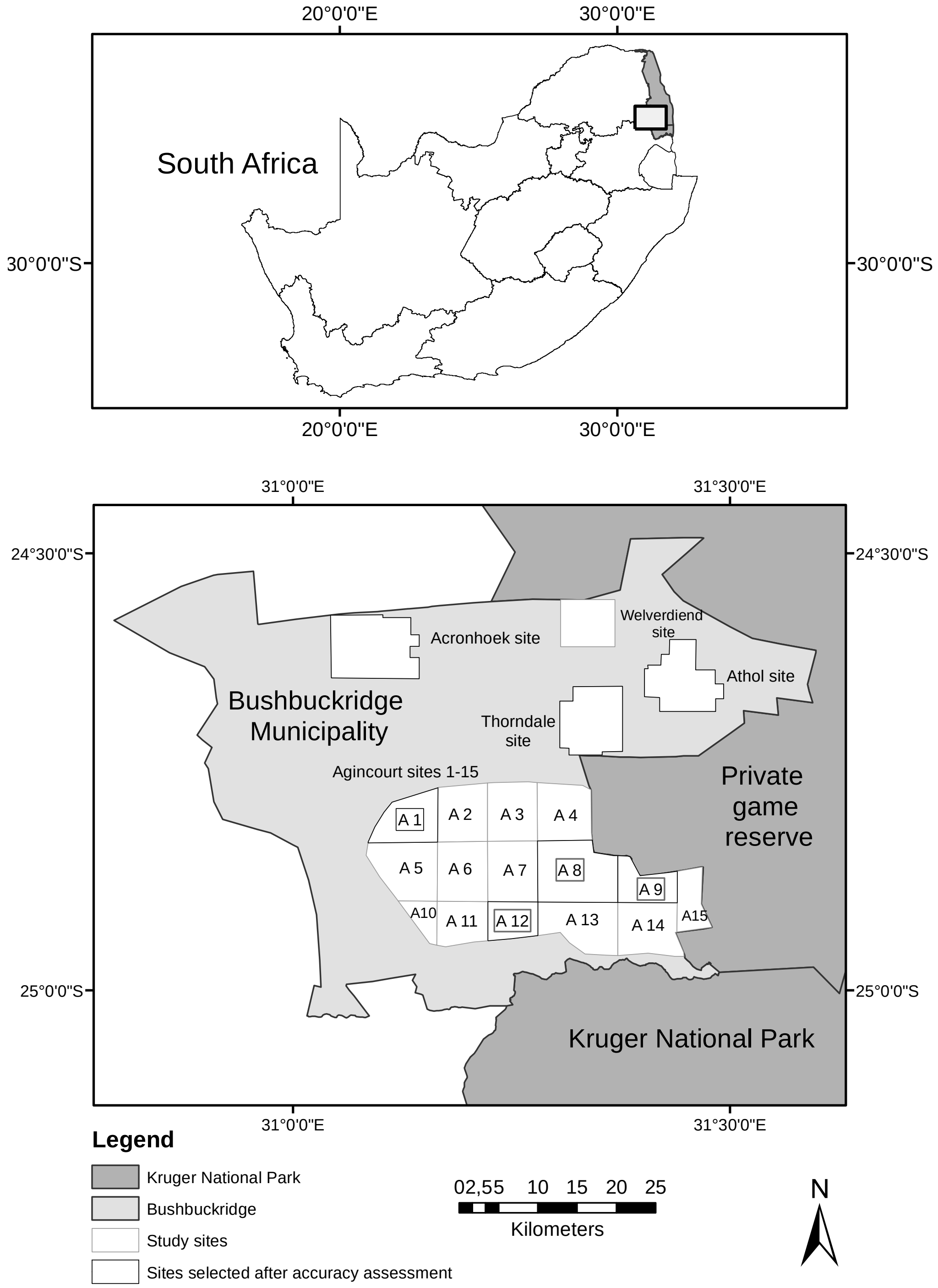

Figure 2.1: The location of Bushbuckridge, South Africa, and the study sites – with the sites deemed usable after the accuracy assessment highlighted with hatching. The 15 Agincourt sites (A1-A15) are sites that are situated within the Agincourt region of BBR

The primary land use to the west of BBR municipality is commercial forestry and to the east it is state and private protected land. The central area of BBR, which is communal land, has a relatively high density of rural villages - which are underdeveloped - and approximately 60-70% of the potentially economically active population is unemployed (Shackleton, 2000). Due to the influx of Mozambican refugees in the 1980s, human populations are high (Shackleton, 2000) and these refugees have become naturalised residents as they are of the same ethnic group as the locals (Shangaan) (Giannecchini *et al.*, 2007).

2.3.2 Data sources

Aerial photographs, captured by National Geo-spatial Information (NGI), were acquired and used as the primary image source. NGI is South Africa's national mapping organization, and is a component of the Department of Rural Development and Land Reform. Images were obtained for three time periods: 1944, 1974 and 2009. Images were acquired covered all of the initial 19 sites, with minimal overlap. The resolutions for the images were as follows; 1944 – 1.65m , 1974 – 1.20m and 2009 – 0.5m. Although the resolutions varied across the imagery, this does impact the results of tree density, since each hectare (the resolution of the outputted tree density) was calculated as a percentage cover, and is therefore resolution independent.

These years were selected as they are 30 years apart and will therefore give adequate time for vegetation change to occur, especially since disturbances can have a lag time before their impacts are fully able to be detected with remotely sensed data, such as we use here. Nineteen forty four was before the *Apartheid bantustan* system was implemented, so this time represents the vegetation before there was a major influx of people. Nineteen seventy four was soon after the major influx of people through the *bantustan* system implementation, which came into legal status in 1959 (Promotion of Bantu Self-government Act, 1959), and was enacted upon in the following years. The 2009 set was 35 years after the previous set, and this was done because it gives an additional 5 years after democratic change, which occurred in 1994, that was a major change in the socio-political landscape.

2.3.3 Image processing

The photographs of 1944 and 1974 were georeferenced and orthorectified. The 2009 imagery was already georeferenced and orthorectified when purchased, so these steps were not necessary. Georeferencing is the process whereby images are given spatial data so that a computer programme (such as a GIS) can place it appropriately on the earth's surface. Orthorectification is done in order to correct for inaccuracies in an image due to lens artefacts and changes in elevation in the earth's surface. Here we used image to image orthorectification (which also georeferenced the image). This method is a type of pseudo orthorectification (or rubber sheeting) because it does not use a digital elevation model to make alterations, but it is sufficient for historical data such as the data we use in this study. The software used for the georeferencing and orthorectification was ERDAS Imagine, version 11.0.3, Build 896 (ERDAS Inc., Hexagon AB, Stockholm).

A reference image was used to perform the orthorectification with the Erdas Imagine software package's Autosync module. The APM (Automatic Point Measurement – an image matching technology that finds corresponding points in two images) Strategy had a column and line increment (the increment in pixels for tie point generation) of 128 and an initial accuracy of 40%, with the manual tie points used for Initial Connection between images. A generic model that simulates the camera system lens – in order to correct for camera lens distortion and abnormalities – is a necessary input, and the Direct Linear Transform (DLT) output geometric model type was used. The Elevation Library was selected as the DTM Source – a built in model that gives data on the earth's surface fluctuations in elevation. A rigorous transformation type was used and the geocorrection (the process of creating the file values for the rectified image) was set to resample with nearest neighbour, with the zeros ignored in the statistics. Correlating points in the sites were used to create the GCP's (ground control points – the tie points between the reference image and the image being rectified). Once the APM was run, sites were moved or deleted until the RMSE error (a cumulative result of point matching and modelling) was under 5pixels. In a few cases this was not possible, but all sites were under 8 RMSE error. A new orthorectified file was then created. These files were then clipped in ERDAS Imagine to the desired area.

Image equalisation was used to perform colour balancing across images. This helps overcome inconsistent colour and brightness problems that are caused in aerial photography by the angle of the sun and lens issues (such as flaring and contrast highlights at edges of image), especially inherent in older photography. Images were balanced individually, then per site, and finally across all sites (after mosaicking), respectively. This sequence led to images free of lens issues and an equal level of brightness (without a bias in a single image – light and dark areas still persist in the landscape), so that later the OBIA ruleset developed would be transferable across images. The Image Equaliser programme in ERDAS Imagine was used to perform the image equalisation, with the brightness set to 109 and the maximum grey shift set to 60, and the minification level set to 1:1 for both the building of statistic tables and the equalisation.

Mosaicking was then done using the MosaicPro programme in ERDAS Imagine to produce one mosaic per site (hereafter referred to as site), with the images stacked in an order that was most suitable for the overlay of images. Overlay-based Seamline was used in the seamline generation (the way in which the programme determines how it produces the pattern where there is the change from the data from one image to the other image).

2.3.4 Woody cover estimation

With the advent of object based image analysis (OBIA), the classification of vegetation in historical remotely sensed data have become a viable proposition. It has been used extensively in recent years for this purpose, as it is ideal for vegetation sampling (Laliberte *et al.*, 2004; Levick & Rogers, 2011; Fisher *et al.*, 2013). The central difference between traditional, pixel based, analysis of remotely sensed data and OBIA, is that information that is contained in the relationship between aggregates of pixels (which become defined objects) can be used for classification. This means that these newly defined objects (such as trees or shrubs) can be classified in terms of spatial arrangement (shape, size, distance to neighbouring objects, association with neighbouring objects and texture) as well as spectral information. For ecological applications, it is more appropriate to analyse objects as opposed to pixels, due to the fact that landscapes consist of patches which can be detected in aerial imagery through OBIA, and not through pixel analysis (Laliberte *et al.*, 2004). The data used in this study consist of black and white imagery for two of the three datasets, and colour imagery for the third. The black and white imagery is of varying contrasts, so analysing these pixels to determine if they are a woody plant or not is not ideal. Therefore, object based image analysis was selected as a method to do this.

eCognition Version 8.72 (Trimble Inc., Sunnyvale, California) was used to perform the OBIA in order to determine woody canopy cover, with each mosaic segmented (Figure 2.2) and classified. Two important parameters in segmentation are compactness and shape. The compactness describes how compact an object is; and is the product of the length and width divided by the number of pixels of the object. The shape parameter defines how much the shape of the object is factored into the segmentation, as opposed to the spectral values. Since the greyscale images had only one spectral variable, the settings were set to use equal values of object shape and spectral value variables; greyscale images had shape set to 0.5, compactness set to 0.5 and scale set to 4. Since the colour images had more spectral information that was leveraged to determine the segmentation, the spectral information was set to be used more than the shape of the objects during segmentation; colour images had shape set to 0.2, compactness set to 0.8 and scale was set to 10. The scale is an abstract term that determines the maximum allowed heterogeneity for the resulting image objects – in practice it determines the size of each object. A trial and error approach was used so that the maximum scale was found that delineates as many of the tree canopies as possible. For each site two classes were created - Trees and Not Trees and samples were selected for each class in a minimum of 10% of the area of each site to gather a training set for the two classes. After the segmentation and manual selection of the resultant objects for use as a training set, the feature optimization tool was used first determine which features of the object are most suitable to classify the images, and then to apply the most appropriate parameters for those features to classify the images. The feature optimisation tool performs a discriminant function analysis to show which features of the training set of objects are most suitable to distinguish the classes. It was used on a single site in each of the year intervals (1944, 1974, 2009) to find the 10 most suitable features to use to differentiate the two classes. A set of features were selected as options from which the tool can select the 10 best fit. The features set as options were selected because they were the most applicable to aerial imagery that mostly consisted of vegetation, where the differentiation of trees and other vegetation is important. The features were selected based on determining their applicability by consulting the user manual. These features were:

- Mean
    - brightness
    - layer 1
    - layer 2 (only for colour images)
    - layer 3 (only for colour images)
    - Max difference
- Standard deviation (applied once for each available layer)
    - Standard deviation
- Skewness (applied once for each available layer)
    - Skewness
- Based on skeletons (applied once for each available layer)
    - Standard deviation of curvature
    - Average branch length
    - Standard deviation of area represented by segments
- Pixel based (applied once for each available layer)
    - Ratio
    - Mean of outer border
    - Border contrast
    - Contrast to neighbour pixels
    - Edge contrast in neighbour pixels
    - Standard deviation to neighbour pixels
    - Standard deviation to circular mean
    - Minimum pixel value
    - Maximum pixel value
    - Circular standard deviation
    - Circular mean
- To neighbours (applied once for each available layer)
    - Mean difference to neighbours (abs)

        - Mean difference to darker neighbours
        - Mean difference to brighter neighbours
- Geometry (applied once for each available layer)
    - Extent
        - Length/thickness
        - Length/width
        - Border length
    - Shape
        - Radius of largest enclosed ellipse
        - Elliptic fit
        - Roundness
        - Compactness

This was repeated for each image for each site, so it was possible that the ten most suitable features weren't uniform across the images. These ten features were then inputted into the feature space optimisation tool again when each site was sequentially processed, and the most suitable five of those 10 features were used to differentiate the classes. Within this tool, the thresholds and parameters were automatically applied to the classes. Then the images were classified according to those classes (which held the parameters that the feature space optimisation tool selected). The results - the two classes of Trees and Not Trees - were then exported as a raster file and imported into ArcGIS Version 10.0, build 2414 (ESRI Inc., Redlands, California), an example of which is shown in Figure 2.2.

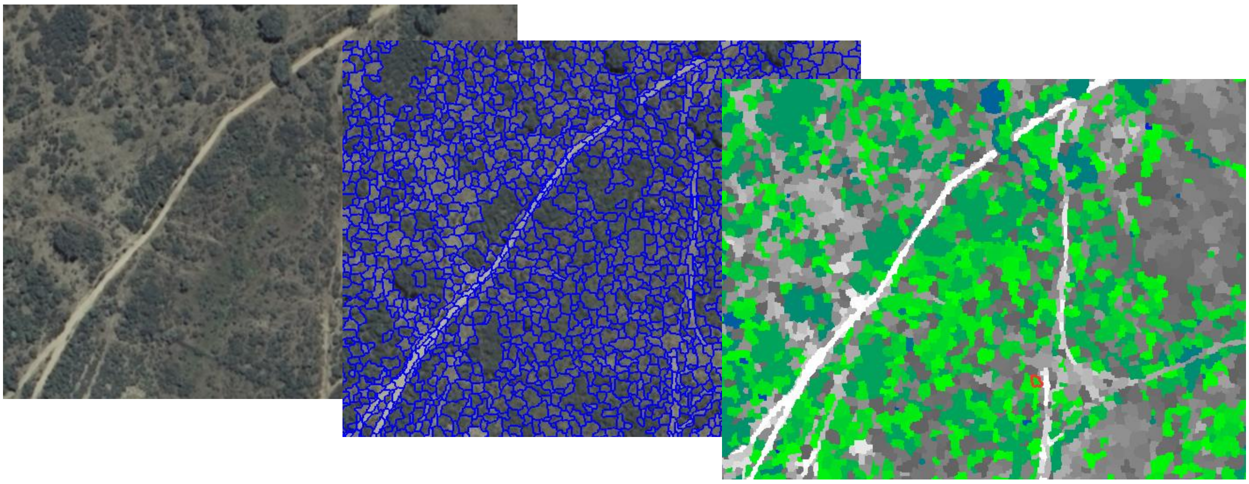

Figure 2.2: An image segmented in eCognition and tree identification using OBIA in eCognition. The green objects are the objects classified as trees, with the darker the green the better it fits the criteria set out in the feature optimization tool.

2.3.5 Accuracy assessment

In ArcGIS, 30 points were randomly generated at each of the 19 sites (using the mosaics generated for each site). This gave a total 570 points across the landscape. These points were used to conduct an accuracy assessment. Each point was assessed by eye for the value (tree or no tree) at that point in the real world, using the raw aerial images. This value was compared to the value ascertained through OBIA, and a confusion matrix was drawn up for each site containing a true positive, true negative, false positive and false negative values. This was repeated at each site for each of the three time periods, resulting in 57 confusion matrices - one for each site at each time period. These were used to generate overall accuracy and Cohen's Kappa statistic (K) for classification accuracy (Cohen, 1960).

It must be noted that Cohen's Kappa is a measure of agreement between items (here, trees identified via software and those visually deemed a tree), once chance agreement is removed. It considers agreement (true positive and true negative predictions), Type I errors of commission (false positives) and Type II errors of omission (false negatives). It is thus useful in a spatial context because there may have been random true classification, in his case by the OBIA algorithm. Table 2.1 provides the accepted benchmarks for Kappa's statistic (Landis & Koch, 1977).

Table 2.1 Interpretation of Kappa's statistic (K) (Landis & Koch, 1977)

Kappa statistic (K)	**Strength of agreement**
< 0.00	Poor
0.00 - 0.20	Slight
0.21 - 0.40	Fair
0.41 - 0.60	Moderate
0.61 - 0.80	Substantial
0.81 - 1.00	Almost perfect

2.3.6 Analysis

Analysis was performed on the images at a hectare level resolution, with percent canopy cover and distance from village calculated for each hectare. Distance was calculated from the edge of the village to the centre of the hectare cell. Data were generated by measuring each village in each time period, and an analysis of patterns of woody canopy cover gave the spatial data on trends in the woody canopy cover at each time period. These data were statistically analysed and compared.

A grid of one hectare (ha) cells was created within the study sites, and statistics on each hectare block were produced, and the number of pixels per hectare block, and the number of pixels that were canopy cover per hectare block, were counted. The number of pixels per hectare block were 3 675 for 1944, 6 945 for 1974 and 40 000 for 2009; the resolutions of the imagery is described in section 2.3.2. These data were imported into Excel 2010 (Microsoft Corp., Redmond, Washington) for analysis. Within Excel, percentage cover per hectare block was generated, with each block having a unique identifier so that it could be compared to itself in differing years.

2.3.6.1 Woody canopy cover in relation to village size and distance from village

In each of the seven sites and at each year, polygons were manually drawn around the villages, and the village area for each site was added as a data attribute for each hectare block, so that it may be analysed statistically. In order to be comparable to Fisher *et al.* (2011), the distance from the village edge to the centre of each hectare block was classified in 200m intervals and added as a data attribute for each hectare block, These data were exported to excel for analysis.

The study sites were additionally divided into two distinct zones for the analyses. These were the northern sites - which include Thorndale, Athol, and Acornhoek - and the southern sites - which include the sites in the southern half of BBR and include the SUCSES sites. They will be referred to as the “northern sites” and “southern sites” respectively, henceforth. This was done because the northern sites tend to be larger (especially Acornhoek), and are closer to the major road systems and towns in the north. This has led to different patterns of human utilisation in the land, and we felt this distinction would lead to meaningful and interesting insights. The northern sites cover 19 120 ha, and the southern sites 16 450 ha; which are roughly equivalent areas.

2.3.6.2 Hot spot analysis of woody canopy cover

A hot spot analysis results in cells (here a cell is one hectare block) being assigned one of five statistically significant (0.05 p-value) cluster types; “hot spots” (areas with adjacent cells of similarly high woody canopy cover), “cold spots” (similarly low woody canopy cover), two types of spatial outliers (a high woody canopy cover cell surrounded by low woody canopy cover cells, and a low woody canopy cover cell surrounded by high woody canopy cover cells) and clusters of non-significant cells. These classes indicate whether the apparent similarity (a spatial clustering of high or low woody canopy cover) or dissimilarity (a spatial outlier) are more pronounced than would be expected in a random distribution. This analysis is a relative measure, and is determined from z-scores and p-values computed during the analysis. From these data, the number of hectare cells of each of the five cluster types was generated, as presented as a percentage of the total number of hectare cells.

For the hot spot analysis, a cluster and outlier analysis (Anselin Local Morans I) was performed on the data pertaining to hectare cells of woody canopy cover percentages for each year (1944, 1974 and 2009), as well as for the tree canopy cover change as a percentage between 1944 and 1974; 1974 and 2009; and the 1944 and 2009 data, This was done with using the euclidean distance method with a distance band of 200m as the distance in order for two cells in each direction to be used in the cluster analysis. The resultant clustering maps were exported using the zonal statistics tool in ArcMap and imported into Excel for analysis. The zonal statistics tool exports a number of basic statistics (e.g. mean, sum) of the pixels within a given “zone” (here the zones were the hectare blocks). With each hectare cell having a unique identifier, specific cells’ cluster types could be identified, and then any changes in that cell's cluster type could be determined. This was done in excel, and only for the high, low, and non-significant cells. These data were used to find which cells persisted or changed their cluster and outlier analysis designation (one of the five cluster types).

2.4 Results

2.4.1 Classification accuracy

Accuracy is the measure of true positives and true negatives in relation to the total number of sample points, whereas kappa is a measure of agreement between true positives, true negatives to their false counterparts, once chance agreement has been removed. Only sites with a K value greater than 0.61 (substantial strength of agreement as per table 2.1) were selected to be used in the study. The only low values were found in the 2009 dataset, in which 12 sites had low K values, and they were excluded from the study. The remaining seven sites can be seen in Figure 2.1.

2.4.2 Woody canopy cover in comparison to village size

The amount of woody canopy cover in the selected sites and the village area increased from 1944 to 1974 and then again from 1974 to 2009 on average across all sites (Figure 2.3). The results for individual sites can be found in appendix A. When the two main areas of BBR (northern BBR and southern Agincourt sites) are separated and their results averaged, it can be seen that the northern villages (Figure 2.4a) show an increase in woody canopy cover from 1944 to 1974, and thereafter a decrease; while the southern sites (b) show no increase in woody canopy cover from 1944 to 1974, and then a sharp increase from 1974 to 2009. Both areas have large increases in village area.

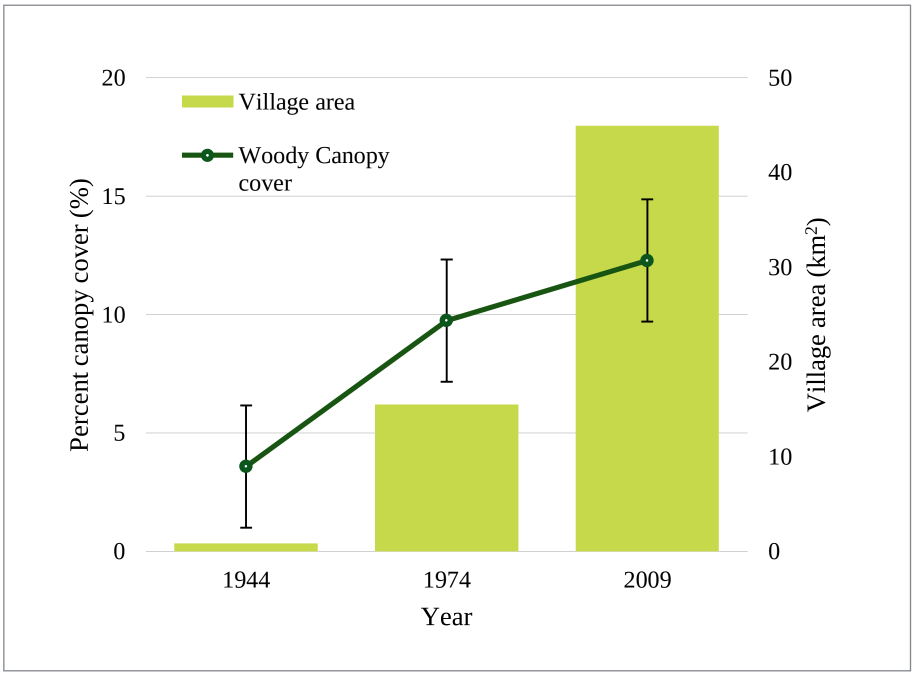

Figure 2.3: Woody canopy cover and village size averaged for all sites

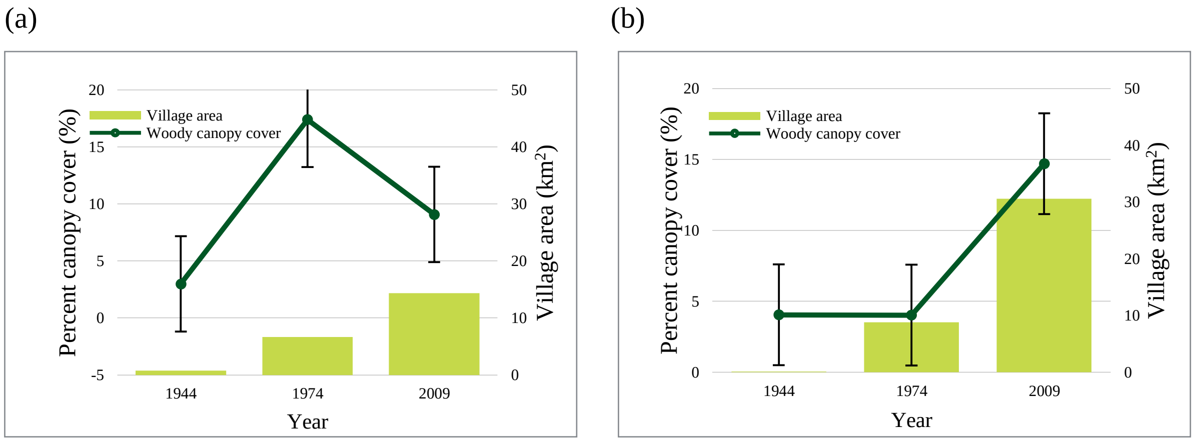

Figure 2.4: Average woody canopy cover and village size for two main areas; the sites in northern BBR (a) and the sites in southern BBR (b).

2.4.3 Woody canopy cover in relation to distance from village

In 1944 and 1974 there was no clear decline in the amount of woody canopy cover with distance from village, and there was a general increase in the woody canopy cover across all distances over time (Figure 2.5). After 1600m there was a slow decline in the amount of woody canopy cover found. In 2009, there was a marked increase in the amount of woody canopy cover found after 1000m. There was a consistent increase in mean percent woody canopy cover inside the villages, form a low of two percent in 1944 to 15 percent in 2009(Figure 2.5).. The increase in woody canopy cover between 1974 and 2009 is larger as the distance from the village increases (Figure 2.5). Appendix B contains the distance from village figures for the individual sites (Figure 2.5).

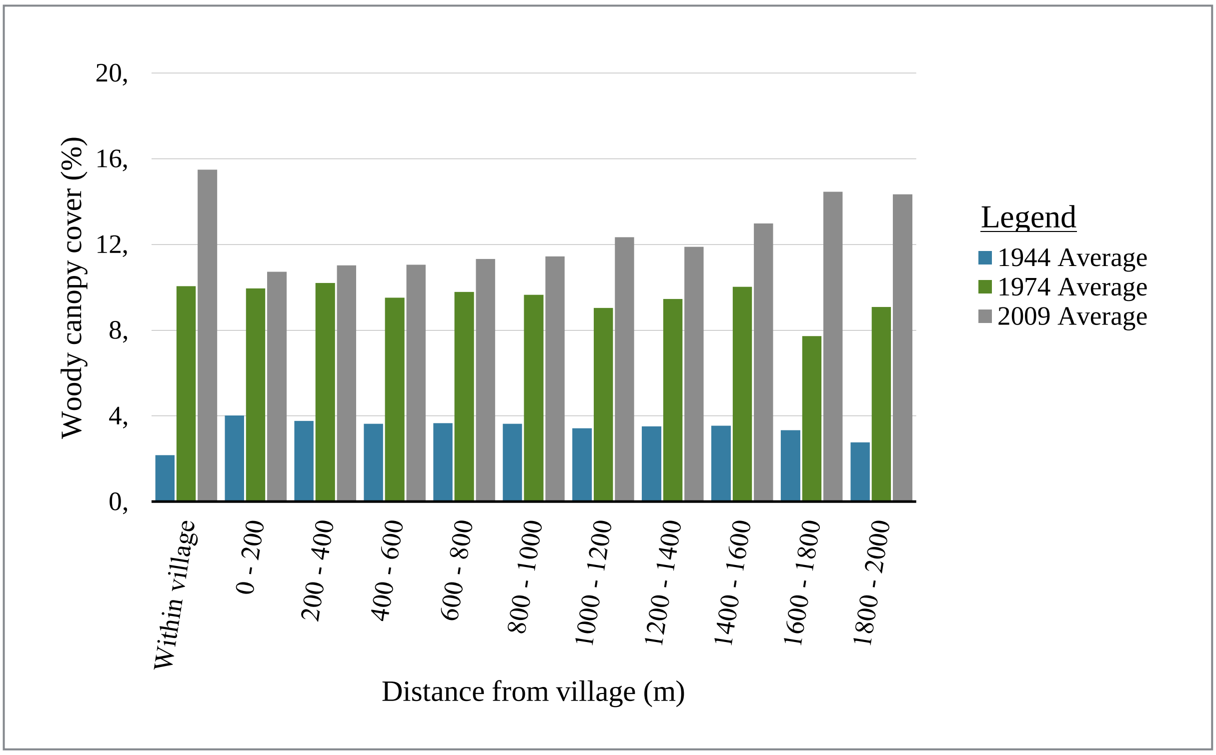

Figure 2.5: Woody canopy cover in 200m intervals from village, aggregated for all villages.

Figure 2.6a indicates that in the northern villages there was a large increase in the woody canopy cover between 1944 and 1974, and then a decrease between 1974 and 2009, however this difference becomes smaller as the distance from the village increases. In the southern sites, there was a sharp increase in trees within villages from 1974 to 2009, and the increase in woody biomass after 1000m is evident, but not as pronounced as in the Northern villages (Figure 2.6). There is very little change in the woody canopy cover between 1944 and 1974 in the southern sites, but a large increase in 2009 (Figure 2.6). In the Northern sites, both in 1944 and 1974 there is a trend of gradual decreasing biomass as distance is increased from village, while in the Agincourt sites there is no trend for those same years(Figure 2.6) .

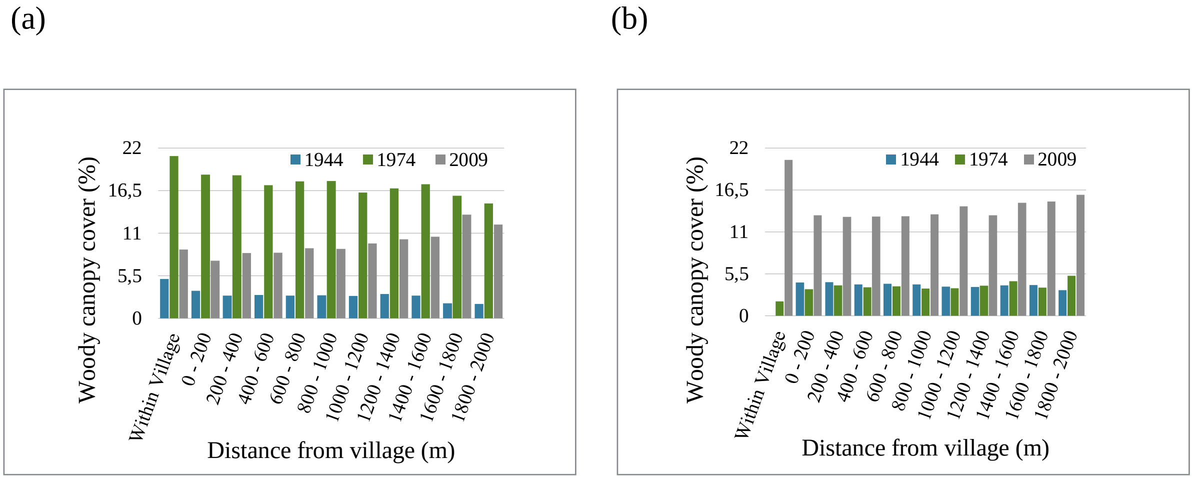

Figure 2.6: Woody biomass cover in 200m intervals from village for a) Northern BBR, and b) the Southern sites (b).

2.4.4 Woody canopy cover clustering and village area

Cells deemed hot spots (high woody canopy cover) and those deemed cold spots (low woody canopy cover) increased in number over the entire study period by 5.5% and 12.5% respectively, while the number of cells deemed non-significant decreased by 18% over the same time period (Figure 2.7). The number of cells deemed outlier clusters remained constantly low throughout the study period. The hot spot analysis charts for individual sites can be found in appendix C.

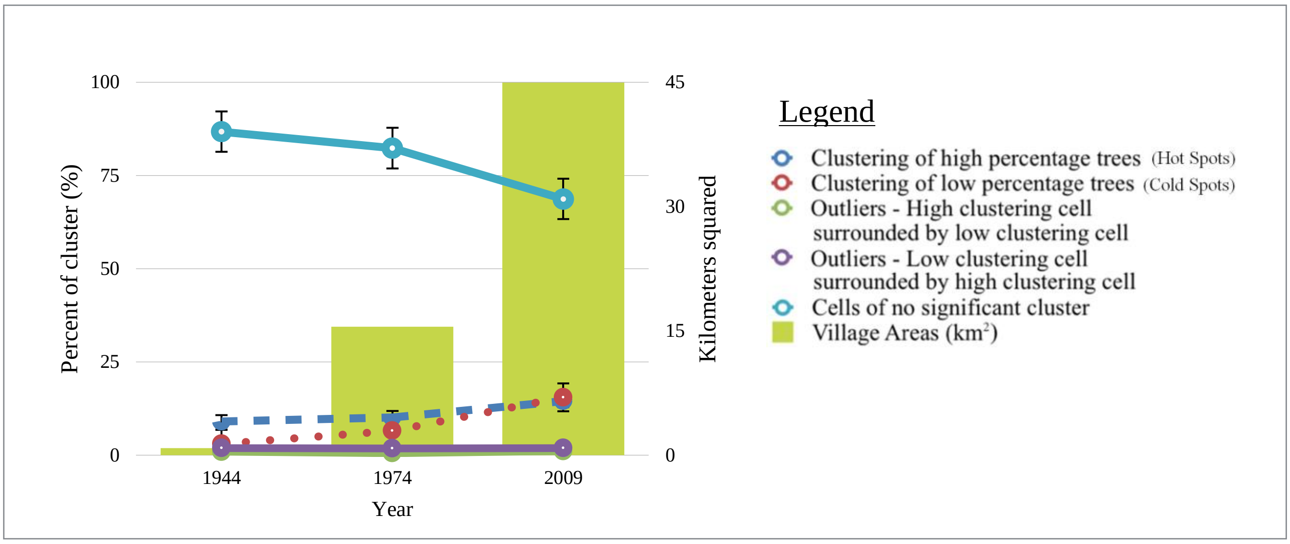

Figure 2.7: Woody canopy cover clustering and village area for all sites.

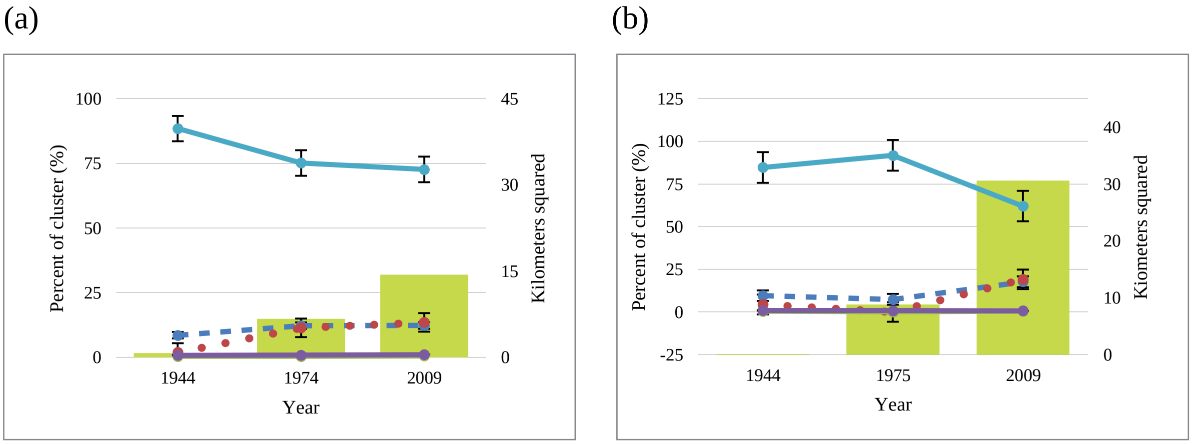

Figure 2.8: Woody Canopy clustering and village areas for a) Northern BBR, and b) Southern sites. The legend follows that of Figure 2.7.

While both the northern and southern areas (Figure 2.8) show a net decrease in cells of non-significant clustering, the northern sites (a) show a decrease between 1944 and 1974 and then another decrease between 1974 and 2009, while the southern sites show an increase between 1944 and 1974, and then a sharp decline in between 1974 and 2009. Similarly, the number of cells of hot spots and cells of cold spots increase gradually across time in the northern sites, while in the southern sites they decrease during the 1944 to 1974 period, and then increase from 1974 to 2009 (Figure 2.8).

Figure 2.9 (a), (b) and (c) indicate an increase in the number of cells of hot spots and cells of cold spots through time in the Agincourt 8 site. In 1944 (Figure 2.9 a), the cells of hot spots occur solely in the riparian areas, with only a small patch of cells of cold spots in the north-east. The small amount of villages is not noticeable at the given scale. In 1974, the village extent has increased dramatically and the amount of riparian cells of hot spots has decreased. By 2009 (Figure 2.9 c), there are very riparian cells of hot spots left, the cells of hot spots are almost exclusively located within the villages. The cells of cold spots have emerged over a large area in the spaces between the villages.

Figure 2.9 (d), (e) and (f) follow a similar trend to (a), (b) and (c), however, there are two differences. Firstly, the area in the east sees a gradual expansion of the cells of hot spots from the riparian zone. Secondly, there isn’t a large increase in the cells of hot spots within the villages in the west, instead they show no significant clustering, a small amount of cells of hot spots or a small amount of cells of cold spots.

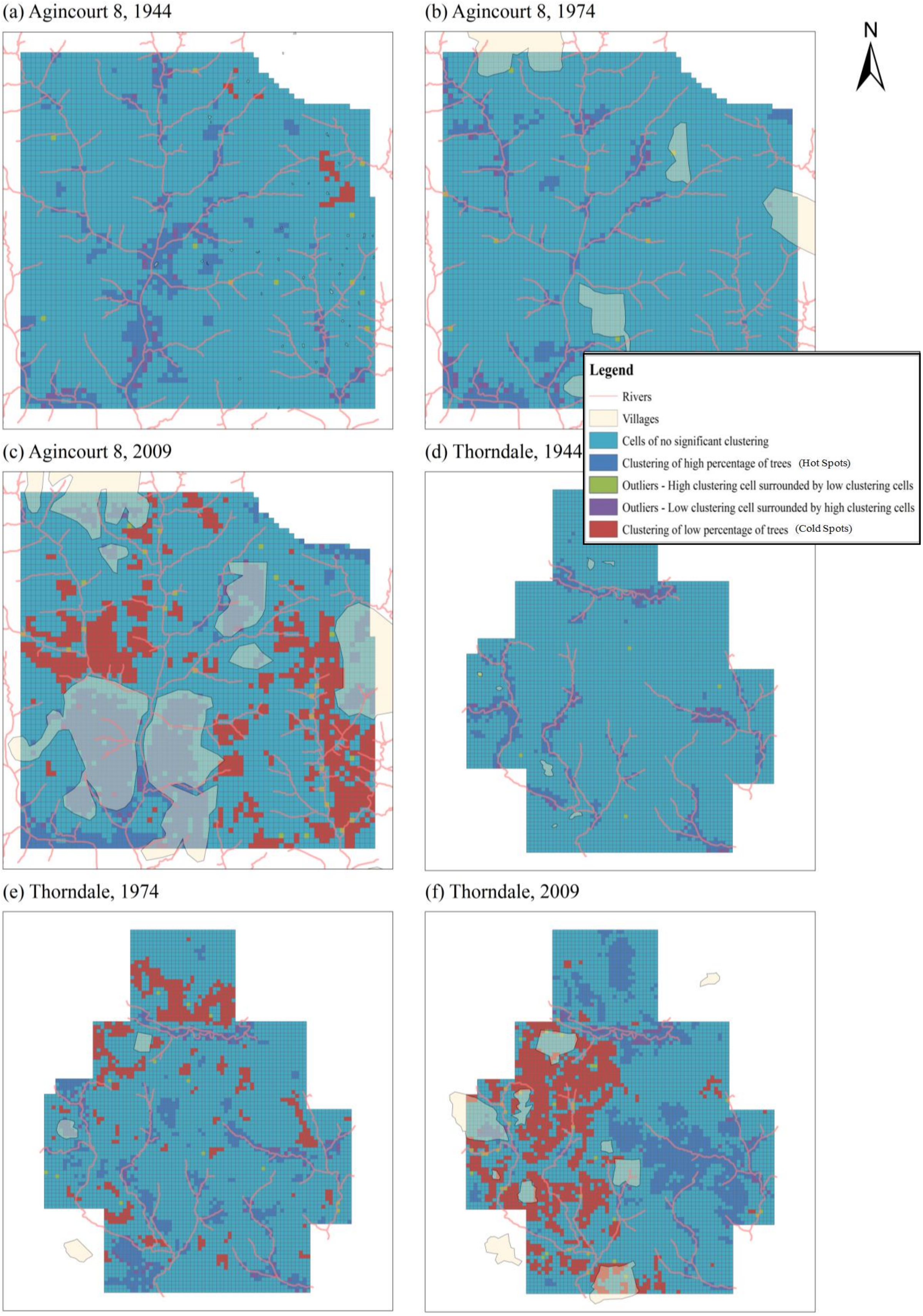

Figure 2.9: Hot spot analysis at two sites (Agincourt 8 and Thorndale) for three time period 1944, 1974 and 2009.

Appendix D illustrates the hot spot analysis for all the sites - these two sites have been selected as two examples typical of our results.

2.4.5 Persistence of hot spots and cold spots

It can be seen in Figure 2.10 that relatively the same amount of hot spots persisted in the two periods of measurement, while more than twice the amount of the cold spots persisted in the second period of measurement (1974 to 2009) when compared to the first period of measurement (1944 to 1974). Over the entire 65 year study period, 12% and 1% of the hot and cold spots persisted, respectively.

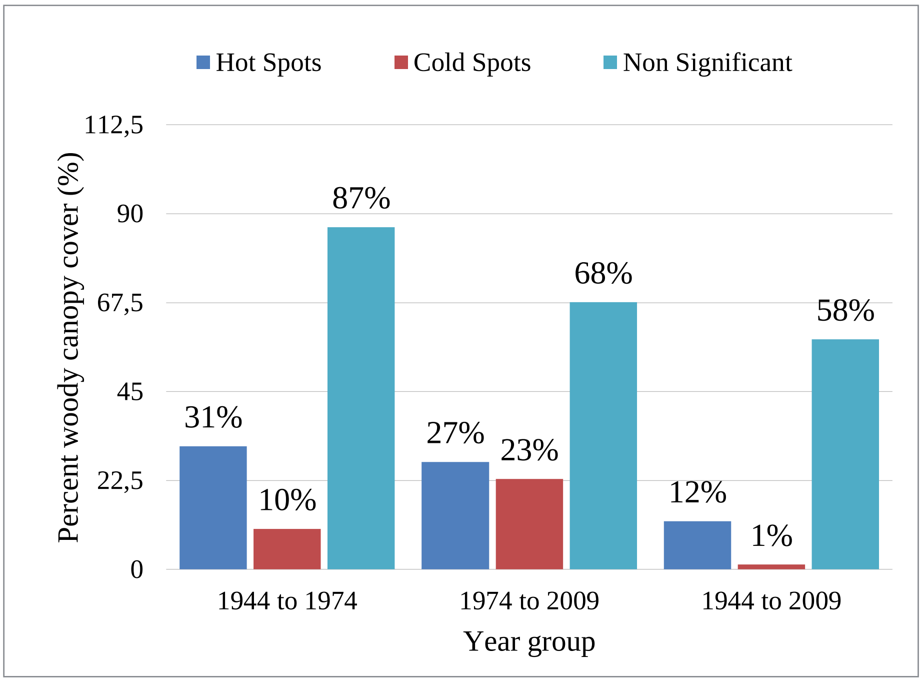

Figure 2.10: Persistence of hot spots, cold spots and non-significant cluster cells across all sites. Percentage is the percentage of a specific type of clusters (e.g. hot spot) of the first year in the time period that are still present in the last year of the time period. This is exact hectare blocks that are still present; new blocks of any given type present in the last year of the time period are excluded.

2.5. Discussion

2.5.1 Overall changes in woody canopy cover

When the data were pooled, there is a trend of woody canopy cover increasing as village area increases. When the sites are separated into two main geographic areas - namely the villages in northern BBR (Thorndale, Athol and Acornhoek sites) and the southern sites in southern BBR - two separate and distinct trends emerge. In the northern villages, there was a steep increase in woody canopy cover from 1944 to 1974, and then an almost equally steep decrease in woody canopy cover from 1974 to 2009. In contrast the southern sites experienced no change in woody canopy cover between 1944 and 1974, and a drastic increase from 1974 to 2009. An increase in woody canopy cover may be attributed to two main factors. The first is the active cultivation and preservation of trees in villages that are known to be of cultural (Walker, 1989), nutritional (Shackleton, 2002; Giannecchini *et al.*, 2007) and economic (Hunter *et al.*, 2007; Shackleton *et al.*, 2007a) importance. The second factor is bush encroachment - an increase in woody plant density in savannas This second factor is explored in more detail below, with regard to the clustering analysis.

Some studies have found that as the fuelwood supply becomes depleted in the area immediately surrounding a village, people walk increasing distances to collect fuelwood (e.g. Giannecchini *et al.*, 2007; Twine *et al.*, 2003a). When villages are in close proximity to one another, their collection base area may overlap - leading to an acceleration of extraction for that overlapping area. In some instances, neighbouring villages will allow collection in their rangelands if they realise that resources are scarce for their neighbours (Matsika *et al.*, 2012). Thus, the sites with higher population densities may be subject to increased harvesting pressure due to this overlap of harvesting areas.

The longer distances walked to collect fuelwood, coupled with weakening control of access the resources and the local economic setting (a local reduction in natural, financial, social and human capital), has resulted in the trade of fuelwood (Giannecchini *et al.*, 2007). This indicates a scarcity of local fuelwood as purchasing of fuelwood is only done once local supplies are low (Aron *et al.*, 1991). At the same time, “outsiders” (people from nearby towns and villages) are harvesting fuelwood for trade (Twine *et al.*, 2003b), which is accelerating the extraction rate in the affected areas. Since the 1994 political shift in South Africa (from the former A*partheid* system to democracy), there is evidence that the collection of fuelwood in this manner has increased dramatically due to a weakening of local traditional authorities (which prior to 1994 had controlled resource extraction) without an increase in capacity for other authorities, such as provincial conservation agencies, to adequately fulfil this role (Twine *et al.*, 2003b; Giannecchini *et al.*, 2007). Once deadwood stocks become diminished and cannot meet demand, live wood is being extracted for commercial use (Shackleton, 1993a; Madubansi & Shackleton, 2007), without consequence due to this weakened control (Giannecchini *et al.*, 2007), mainly by outsiders (Grainger, 2009). This may explain why, in the northern sites, there has been a sharp decrease in woody canopy cover in the 1974 to 2009 period. Most of the studies here on this subject were undertaken primarily on villages in northern BBR (e.g. Giannecchini *et al.*, 2007; Matsika *et al.*, 2012). It may be that these northern sites' rangelands are under far higher pressure for natural resources, due to their close proximity to a main road (Orpen road), where people can transport collected fuelwood more easily. The southern sites may be under less pressure from outsiders due to their relative remoteness, but this may change if the resources in the north become exhausted.

Our results match those of Giannecchini *et al.* (2007), in the trend of decreasing woody canopy cover for two of the northern villages that were also included in that study (Thorndale and Athol) for the 1974 to 2009 period of analysis, but that study was only undertaken on 1974 to 1997 data. Despite this, their data were decadal and they found that the trend of changes in land cover was not linear at a village scale and that in some cases the change reversed. Our data show that at a larger temporal scale the trend in woody canopy cover coverage is indeed nonlinear and rapidly reverses (in our case in 1974 for the northern sites). Additionally, while there is much focus on the rapid loss of woody biomass in northern BBR due to unsustainable harvesting (Banks et al., 1996; Giannecchini *et al.*, 2007; Matsika *et al.*, 2012, Wessels *et al.*, 2013), it should be noted that the current levels of woody cover are far higher than levels were in 1944 when the land was far less disturbed, and that the region may be experiencing a decline in woody biomass after a long period of increase - as our data indicate. This may indicate that bush encroachment and coppicing are, at a landscape level, countering "deforestation". This is discussed in more detail below.

2.5.2 Disturbance gradients

Recent studies have found that with increasing distance from villages in BBR, there is an increase in woody biomass (Shackleton *et al.*, 1994; Banks *et al.*, 1996; Fisher *et al.*, 2011; Wessels *et al.*, 2013). Our data show a similar result of a disturbance gradient in 2009, with a relatively stable amount of woody canopy cover from the village edge to 1000m, and thereafter a general increase to 2000m. There was, however, no apparent trend in 1944 and interestingly an opposite trend in 1974; woody canopy cover was stable up until 1600m from the village and thereafter decreased to 1800m.

This may be due to light harvesting from the village to the 1600m causing coppicing, resulting in a perceived increase in woody canopy cover in these classes. This trend is only strongly visible in the northern sites, while there is no trend in the southern sites - probably due to the Agincourt sites in the south being less established at that time. Trends visible in 1944 are most probably due to the natural vegetation patterns because the landscape was not heavily utilized by humans at that point in time. However, in 1974 there was a large increase in human disturbance, as seen in the increase in village size, and from then onwards an extraction gradient developed. The hot spot analysis reveals that cold spots (which are probably a result of harvesting) do not appear closer to villages in 1974 and then spread further from them in 2009 - as would be the case if disturbance gradients develop slowly over time. Instead, we found no cold spots in Agincourt until 2009. In Thorndale, cold spots emerge in 1974, but they are spread throughout the study site.

We found that the presence of a disturbance gradient is settlement-specific, and the presence of a general trend across all sites is interesting when looking at the analogous charts for individual sites (Appendix B). Our data show that in at least one site (Agincourt 9: Appendix B, f) there is a disturbance gradient in 1974 and 2009, while at the Athol site (Appendix B, b) there is no gradient in any year. Fisher *et al.* (2011) also found that disturbance gradients are settlement-specific, and that highly utilised rangelands can result in the disappearance of a disturbance gradient. As Giannecchini *et al.* (2007) point out, these landscapes are dynamic, with local socio-economic and biophysical factors playing a major role in shaping the landscapes. In order to assess the drivers of these patterns, far more data are needed than are presented here, but a more detailed look at drivers of these patterns can be found in chapter 3. Additionally, it should be noted that these results may be confounded by the nature of the collection of data in this study: in that specific outlines of the edges of villages were demarcated, so that they formed a series of polygons. Thus, the areas between multiple polygons were included in the distance measurements which overlap (and the closer distance used). However, it is interesting to note that at a landscape level, a disturbance gradient is apparent, but only in the 2009 data. This suggests that the phenomenon is driven by factors that have only become prevalent in the period between 1974 and 2009, or that it is a result of the increase in woody biomass that has occurred between 1974 and 2009.

2.5.3 Harvesting, bush encroachment and protection of trees in settlements

We found an overall trend of an increase the amount of cells, and the size of groups of cells (as seen in the map in Figure 2.9), of hot and cold spots, as well as a decrease in cells of non-significant clustering, throughout the 65 year study period. This indicates that the landscape is being heavily impacted upon.

An increase in cells of hot spots may be due to two factors. Firstly, within settlements, trees in yards are planted and protected in order to use their produce to supplement food and/or income (Shackleton *et al.*, 2003), or for cultural reasons (Walker, 1989). This is clearly visible, and has been observed by the author, from the raw aerial images and from ground observations. This results in a higher density of large trees inside settlements, as opposed to outside where they are vulnerable to harvesting and fire. Five out of the seven sites investigated in this study (Thorndale, Acornhoek, Agincourt 8, Agincourt 9 and Agincourt 12) displayed this increase in hot spots within settlements, showing that it is a common practice among the villagers in the area.

Secondly, for communal land, bush encroachment may be the cause of an increase in hot spots of woody canopy cover. Bush encroachment is a large and well documented problem which serves to drastically increase woody plant biomass, at the expense of palatable grasses and herbs (Ward, 2005). Bush encroachment is a problem in South Africa because it affects the agricultural productivity and biodiversity of 42% of the countries magisterial districts, and it has been observed that large areas of South African savanna have declined from economically viable livestock properties, to ones that are not economically viable (Donaldson, 1980; Hoffman & Ashwell, 2001). This makes it a biodiversity and an agricultural problem (Ward, 2010). The classical understanding of bush encroachment is that the causal factors are driven by the local disturbance regime (Buitenwerf *et al.*, 2012), either heavy grazing or fires (Hoffman & Ashwell, 2001). The problem is considered particularly severe in the communal rangelands of South Africa where there is continual heavy grazing (Walker, 1981). Additionally the low cost solution of killing trees is the least economical in the long term (Smit, 2004) - a cause for concern in an area with low economic activity. Whilst the spatial pattern and relative ratio of grasses and trees in savannas are determined by a complex interaction of soils, geomorphology, fire, climate, topography and herbivory (Backéus, 1992), the causal factors of bush encroachment (which leads to a shift in this ratio) are under continual deliberation. Water has typically been assumed to be the limiting factor for both grasses and trees in savanna systems - leading to a separation of rooting niches, the idea stemming from Walter's (1939 and 1971) two-layer hypothesis (Ward, 2005). This hypothesis has been deemed inadequate by some authors (Scholes & Archer, 1997; Ward, 2005), and many are now attributing bush encroachment to variations in fire and rainfall intensity (Higgins *et al.*, 2000), cyclical succession regimes (Wiegand *et al.*, 2006) and atmospheric CO_2 changes (Ward, 2010;

Buitenwerf *et al.,* 2012). The number of plausible theories for the savanna tree grass interaction is increasing, but these theories tend to be scale free (Wiegand *et al.,* 2006).

Here we present data on 65 years of savanna woody canopy cover that show that, in that time scale, the trend appears to be a general increase in bush encroachment in areas that are less influenced by nearby anthropogenic factors (proximity villages). Cells of hot spots of woody canopy cover are only present as riparian vegetation in 1944 in Thorndale. By 1974, cells of hot spots appear in the open areas close to the rivers and by 2009 they represent a substantial amount of the land cover in the eastern part of the Thorndale site. The western part of the site is dominated by cells of cold spots of woody canopy cover, this may be due to the villages only being present in the western half of the image, and thus the harvesting of woody biomass being concentrated in that section. This demonstrates that bush encroachment is occurring in areas that are not close to villages (where heavy harvesting is occurring), but a distance that is possibly where cattle and other livestock and sent to graze. In the areas close to villages, harvesting may be mitigating the effect of bush encroachment. It must be noted that the Thorndale site is the furthermost eastern village in BBR, with only communal land and a private game reserve to the east before a border with a national park (Kruger National Park).

There are also large areas where cells of cold spots of woody canopy cover are present in the study sites. Cells of cold spots increased by 12.5%, compared to cells of hot spots which increased by 5.5% throughout the study period of 65 years. It has been reported in numerous studies that harvesting of natural resources is occurring in this area at a high rate (High & Shackleton, 2000; Shackleton *et al.,* 2001; Dovie *et al.,* 2002; Dovie *et al.,* 2004; Kirkland *et al.,* 2007). Harvesting of woody biomass would result in open areas, which would be detected as cells of cold spots using the methods employed in this study. As aforementioned, the increase in cells of cold spots appears to be in areas close to villages. This suggests that this increase is due to the harvesting of woody biomass and browsing by goats occurring at a faster rate than coppicing regrowth around villages, and can be seen in the 2009 images.

While the overall amount of woody canopy cover increased between 1974 and 2009, the difference between 1974 and 2009 is greater further from villages. The amount of people utilizing the land in 1974 may have meant that they would have been expanding to the areas furthest from the villages, and utilizing that land heavily for woody tree extraction and clearing for grazing lands. Therefore, in 1974 the furthest areas would show a lower amount of woody canopy cover. By 2009, that area would have coppiced and be subject to bush encroachment, and show a higher amount of woody canopy cover, relative to the areas closer to the villages. It would be of interest to expand this study show what drivers were important in determining the woody canopy cover, and how those drivers acted upon the woody canopy cover (e.g. if high rainfall influenced patterns of hot and cold spots as much as low rainfall, through time).

Of the seven sites examined in this study, all had an increase in cells of hot spots (bush encroachment and planting of trees in residential areas) and cells of cold spots (removal of woody biomass for fuelwood) in the areas outside the villages. The overall area occupied by the villages has increased over the study, most drastically between 1974 and 2009. Similarly, the increase in cells of cold and hot spots has also increased most drastically over that same time period. This indicates that the area has been heavily impacted upon, most plausibly by anthropogenic causes, and that the trend has not yet stabilised. When looking at the southern sites separately, it can be seen that from 1944 to 1974 there was a decrease in cells of cold spots, and a slight decrease in cells of hot spots. This may be because these villages were established later than those in northern BBR, and thus did not have an impact on the surrounding landscape in terms of harvesting and bush encroachment until after 1974. This is in contrast to the northern sites, which experienced an increase in cells of low and high clusters from 1944 to 1974, and then relatively little change from 1974 to 2009 - showing that these villages became established and impacted their surrounds earlier in time than the sites in the South.

2.5.4 Persistence of areas of hot and cold spots of woody canopy cover through time

Throughout the study period, the percentage of cells of hot and cold clusterings that persisted is low. Only 12% and 1% of cells of hot and cold spots, respectively, present in 1944 remained in 2009. Fifty eight percent of the cells of non-significant clusterings that were present in 1944 are still present in 2009, meaning that a large portion of them have been changed into another form of clustering over the 65 year period. This is alarming in that it suggests a landscape that has been heavily disturbed. Between 1944 and 1974, a higher percentage of the cells of non-significant clusterings persisted than from 1974 to 2009 (87% versus 68%) - which may indicate that in the first period of measurement there was less expansion of cells of hot and cold spots into areas previously occupied with cells of neither hot nor cold spots. If the causes for the disturbance are anthropogenic, this increase in disturbance through time would be parallel to the increase in human population - which is seen in an increase in village size. Figure 11 is “backward looking” in that it depicts all the cells present in 1974 and 2009, separately, and then displays what percentage are new cells, and what percentage have persisted from the designated previous year of measurement (designated on the x-axis). It shows that in 2009, 100% of the cold spot cells are new (this number is actually above 99,5% and has been rounded up), and that 92% of hot spot cells are new. This can only be possible if the vegetation is in a state of change through time. This is confirmed when looking at the hot spot cells in 1974, only 27% are from 1944, and in 2009 only 18% are from 1974. Similarly, regarding cold spot cells in 1974; only 8% are from 1944, and in 2009 only 12% are from 1974. Overall, this depicts a landscape where there is continual change in vegetation abundance, not just at a landscape level, but at a local, Hectare resolution, level.

2.5.5 Changes in woody canopy cover in comparison to predictions by other authors

Banks *et al.* (1996, p. 319) stated that within 15 to 20 years of the date of that publication, the villages of Welverdiend and Athol would be in a state of "severe deforestation." Given that the population has grown at the three percent (they estimated growth rate using household counts four years apart) used in their model, the data we present show that Athol has not suffered the predicted outcome by Banks *et al.* (1996), nor have any of the other villages in this study. This is in spite of severe removal of woody canopy cover has occurred in at least one of these villages (Athol), This finding is mirrored by Matsika *et al.* (2012), who found that woody biomass has decreased around Athol by 12% between 1992 and 2009, which is roughly what the data we present show. Our data show that there has been a loss of woody canopy cover at the Athol site, but that it has not returned to its 1944 level.

While the level of woody biomass is still high, it must be noted that it may be that the structure of the woody biomass has changed, as Matsika *et al.* (2012) found. A study by Fisher *et al.* (2011) found that intense use resulted in homogenisation of woody plant size classes. Additionally, coppicing of trees and bush encroachment may exacerbate this homogenisation. Therefore, the intense use has probably changed the structure of the woody vegetation, but the standing crop of woody biomass may not be reduced by as much as was predicted, and so the model given by Banks *et al. (1996)* has proved to be non-predictive. A change on the structure of the woody biomass may have negative ecological consequences, which may only be seen in the long term future. This may be important in analysing human-environment interactions in savannas - in that they have been shown to be dynamic and resilient as far as the standing woody biomass crop is more stable than predicted.

2.6 Conclusion

Most surprisingly, we found that the absolute amount of woody canopy cover has increased in these communal lands through time, because authors had suggested that with an increase in human population, and thus disturbance, would lead to a decrease in woody canopy cover (Banks *et al*., 1996). Also, it is highly probable that the structure of the woody vegetation has changed dramatically to that of a lower, shrubbier, coppicing landscape. This is supported by the fact that only a very small amount of the hot spots and cold spots have persisted throughout the 65 year study period. This may indicate a landscape that is highly dynamic– patches of hot and cold spots appear, disappear and then reappear, while overall there was an increase in both hot and cold spots. The reason for this may be that areas of high woody canopy cover are harvested, and then a coppice response ensues. In this way, the spatial patterns detected by the hot spot analysis tend to support the gradient analysis – in that hot and cold spots in early imagery disappear, and new ones are formed in later imagery. This shows that the patterns of woody canopy cover are dynamic and highly variable in space and time in the former *bantustan* South African savannas.

The data suggest that initially a disturbance gradient develops due to increasing harvesting and clearing for fields, and as this intensifies in time as the population grows, this gradient becomes less steep. Eventually a point is reached where harvesting and clearing causes the gradient to flatten out and disappear – leading to a low amount of coppicing trees, detected in this study as an increase in woody canopy cover.

Bush encroachment and a loss of woody vegetation, possibly due to harvesting by humans, have had a profound impact on the landscape. When considering that an increase in human population brings more pressure on the surrounding environment through more harvesting and bush encroachment due to grazing, the parallel increase in woody biomass and human population found here points to a human-impacted ecological system. Indeed, our findings are village-specific and not homogenous, since human-environment interaction is not homogenous. Our data show that scale is an important factor in savanna systems, and that different trends are apparent at both fine and broad spatial and temporal scales. Whilst many studies focus on a limited spatial or temporal scale, or in some cases both, here we demonstrate that when focusing on change in vegetation, it is imperative to select a scale that is appropriate to the scale at which drivers of that change operate. For example; the village of Acornhoek had a dramatic increase in woody canopy cover form 1944 to 1974, and then an equally dramatic decrease in woody canopy cover form 1974 to 2009. If a study was done between 1974 and 2009, it would appear that the woody canopy cover is decreasing through time. However, by incorporating the 1944 to 1974 data we find that the net change is almost zero; hence a large temporal scale is necessary. Then, to consider spatial scale; if we expand our example to include the seven sites used in this study, it becomes clear that this trend is not apparent across the landscape (as these sites were spread across BBR), and the net change through the study period was an increase in woody canopy cover, contrary to the Acornhoek where there was almost no change; hence a large spatial scale is also absolutely necessary to get accurate results. However, we do acknowledge that access to data and time to process data on large areas and time scales will steer decisions on scale away from what is ideal. This will undoubtedly change as computer processing costs come down, and the speed of processing data increases.

The methodology employed in this study is subject to a number of constraints. Foremost is that it can only detect woody canopy cover, and not actual woody biomass. This is especially important because of the way in which savanna species of trees coppice. It may be that the actual biomass of an area has decreased, due to harvesting of tree species, but due to coppicing the woody canopy actually increases. This constraint may be especially pronounced in older aerial imagery (such as the 1944 data set used here), because OBIA is not able to detect canopy cover as accurately as in the newer, higher resolution imagery. Coppicing and bush encroachment are inferred through the gain and loss in woody canopy cover, respectively, and through the spatial patterns that emerged thereof. We do feel that although these constraints exist, the methodology employed here is suitable to perform these studies, if they are taken into consideration when comparing our results to those found through other methodologies. While this study serves to document the spatial trends in woody canopy cover that have shaped the BBR savanna landscape, it would be of great value for research to be undertaken on the drivers that have caused these trends across a long term temporal scale. This has been undertaken in chapter three, and these drivers help shed light on how the landscape functions, and are an important addition for savanna systems ecology. Additionally, the findings of this study may help in studies that aim to predict future trends in woody biomass. The spatial scale of an ecological study can have vast impacts on its finding (Wiens, 1989), and while Giannecchini *et al.* (2007) notes that scale is of vital importance in human impacted savannas, this study demonstrates that with current computing abilities studies can be undertaken with a broad scale and a fine resolution - effectively giving both landscape and local level results. The same is true for temporal scale - trends uncovered at smaller temporal scales were previously extrapolated and applied across larger temporal scales, here we show that trends may be temporally dynamic in nature. In order to make more accurate ecological findings, future research will be well served to include a spatio-temporal scale of a magnitude appropriate to the ecological and anthropogenic processes that may be at work. This is because the ecological processes we are testing for here may occur over large periods of time (decades to centuries), and there may be a lag phase between when an impact occurs and when it may be measured. Anthropogenic processes are similar, and additionally they are dynamic in that they may fluctuate over small time scales, and thus a large temporal scale is necessary for meaningful measurement.

Spatio-temporal understanding of ecological systems dynamics is lacking in many areas, especially spatio-temporal heterogeneity, yet it is fundamental to its conservation and management (Levick and Rogers, 2011). Since this area is home to a large population of people which rely on the environment for a number of ecological services, the sustainability of the natural resource base is of great importance, and more research is needed on what has driven, and continues to drive, these long term trends. Changes in the woody biomass do not occur in a predictable, linear fashion, and although we have speculated in this paper what the drivers may be, determining them will inform management for sustainability purposes. The results we obtained here may be useful in establishing a baseline for trends in woody biomass change in the area, to which data in other similar areas may be compared. Additionally, it may be useful to compare these trends to year on year data to produce more informed monitoring outcomes. In this way an early warning detection system may be developed, using OBIA to monitor annual changes in woody canopy cover – especially when using new, high resolution data where OBIA yields very good results.

2.7 References

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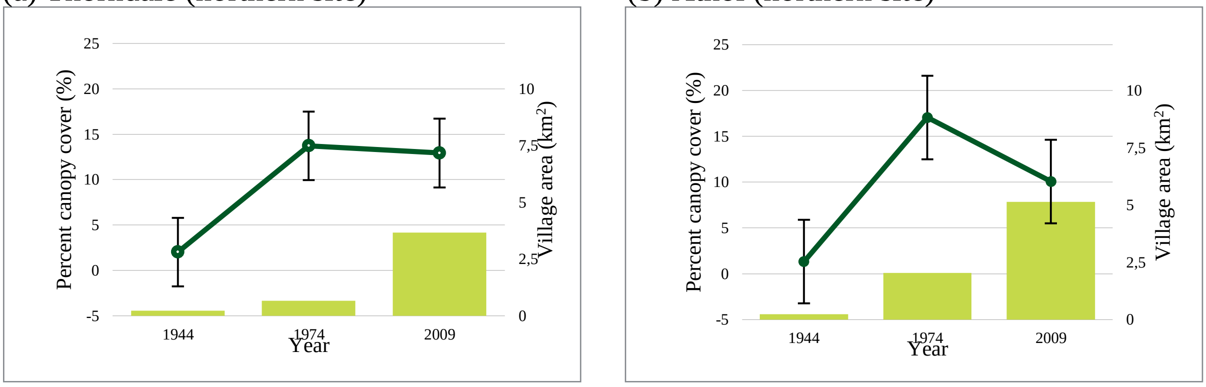
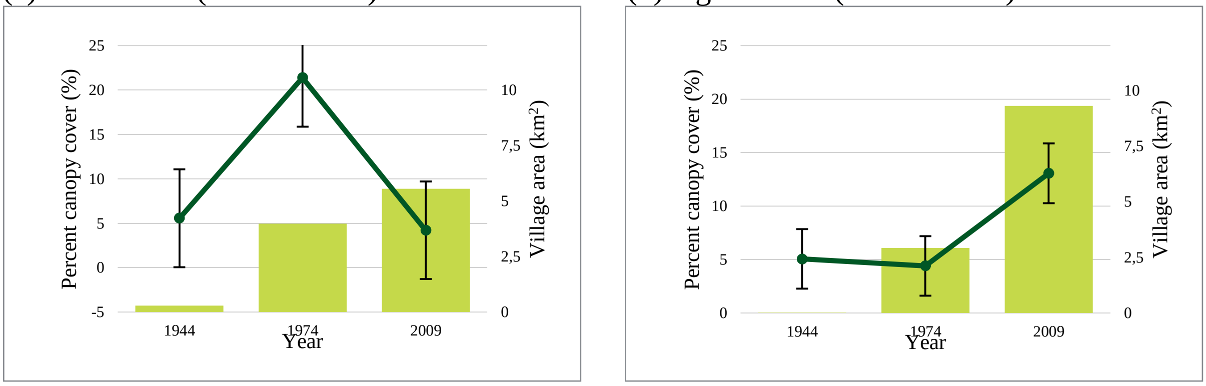
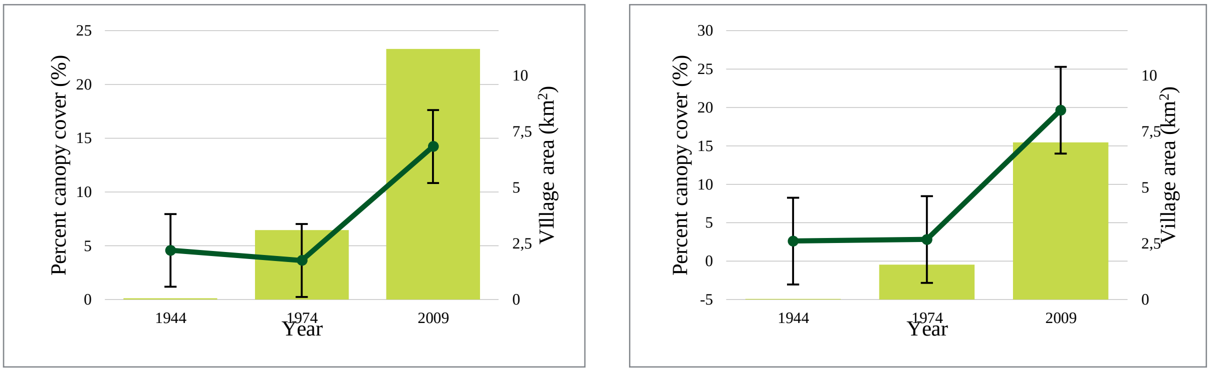
2.8 Appendices


(a) Thorndale (northern site)

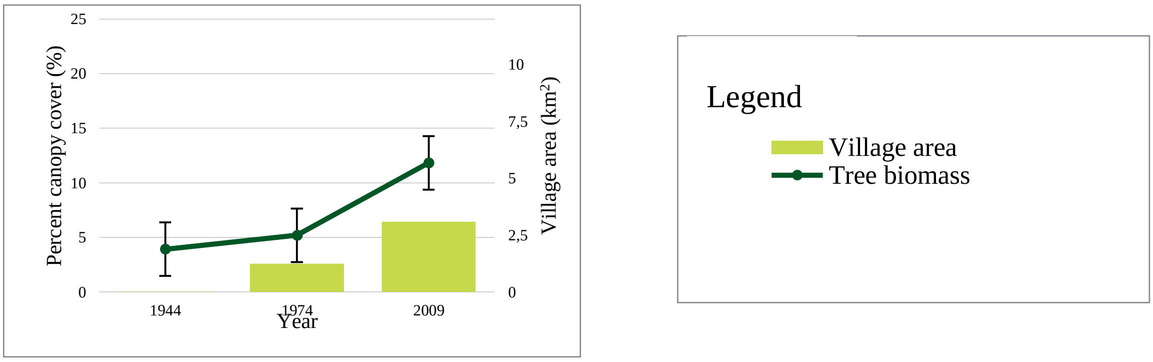
(b) Athol (northern site)


(c) Acornhoek (northern site)

(d) Agincourt 1 (northern site)


(e) Agincourt 8 (southern site)

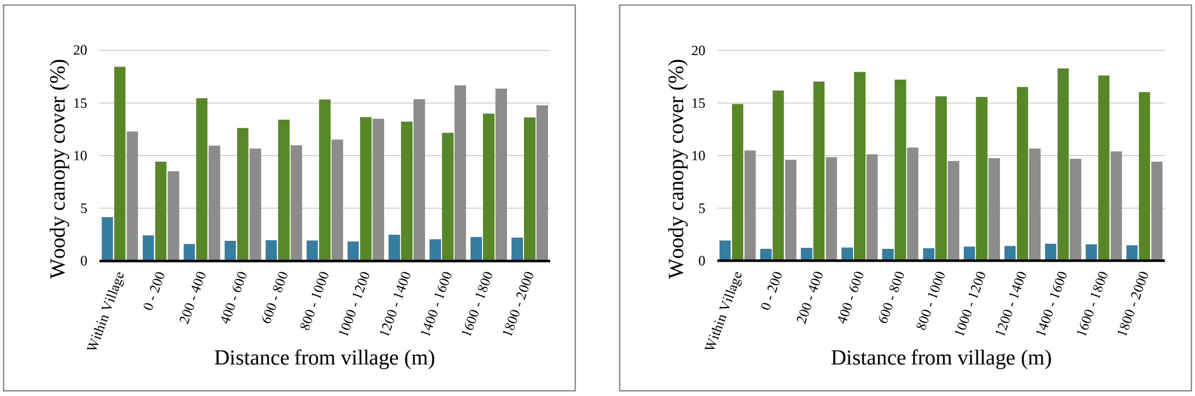
(f) Agincourt 9 (southern site)


(g) Agincourt 12 (southern site)

2.8.1 Appendix A: Woody canopy cover in comparison to village size for individual sites

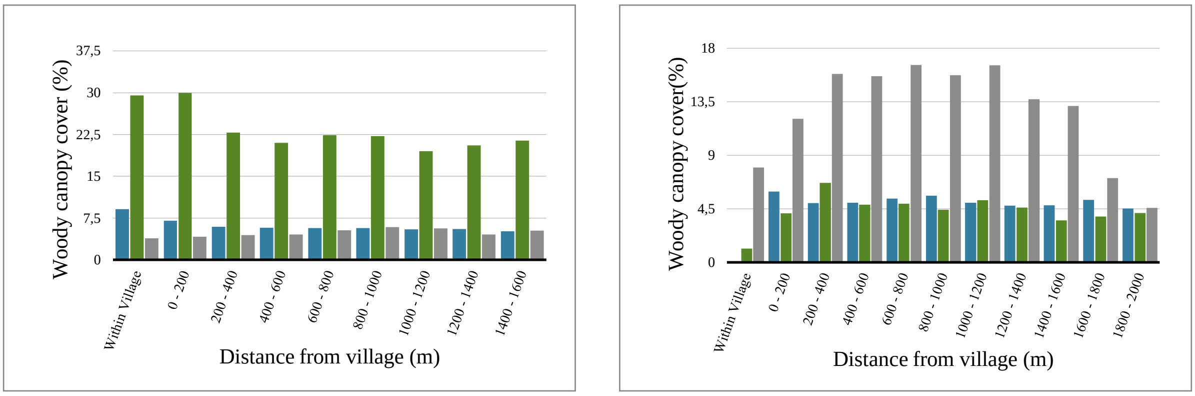
(a) Thorndale (northern site)

(b) Athol (northern site)



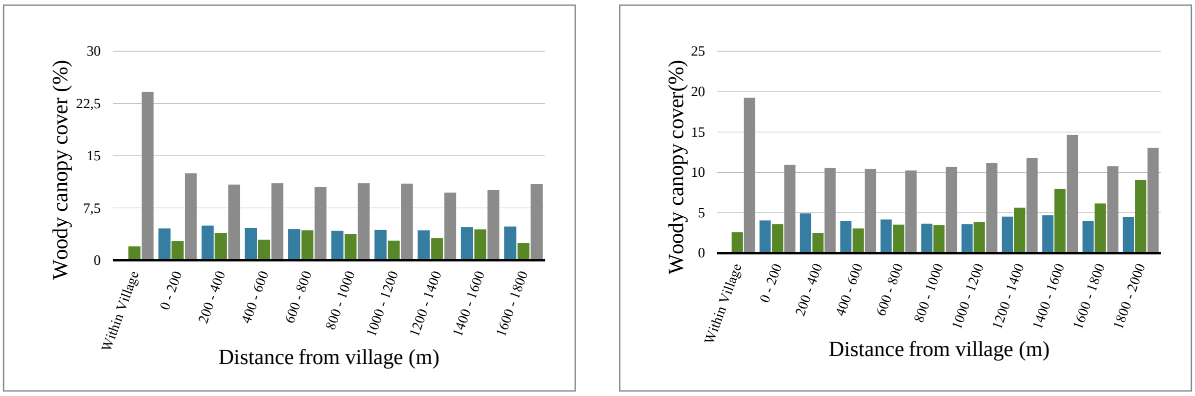
(c) Acornhoek (northern site)

(d) Agincourt 1(northern site)

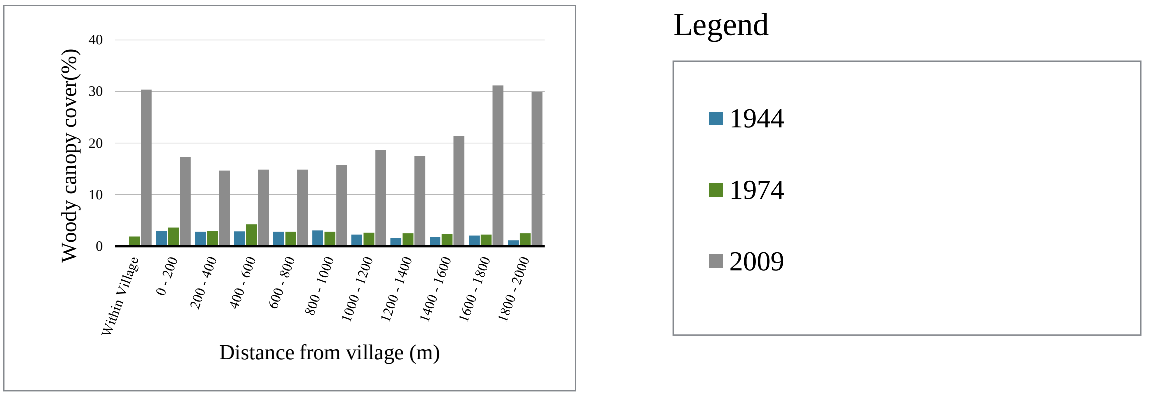


(e) Agincourt 8 (southern site)

(f) Agincourt (southern site)

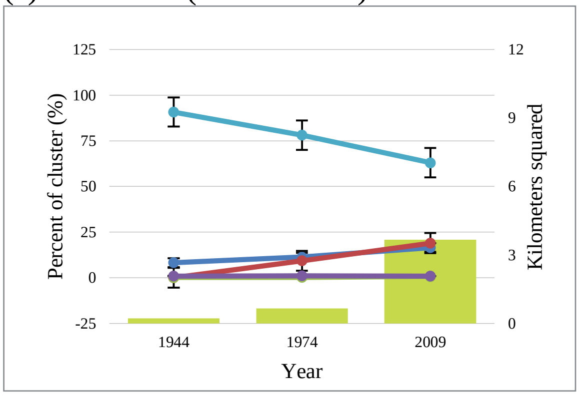


(g) Agincourt 12 (southern site)

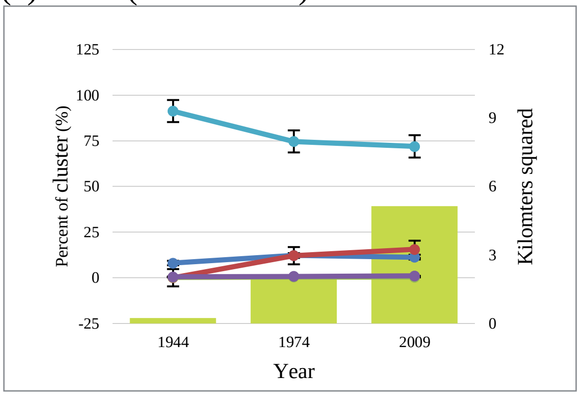


2.8.2 Appendix B: Woody canopy cover in relation to distance from village for individual sites

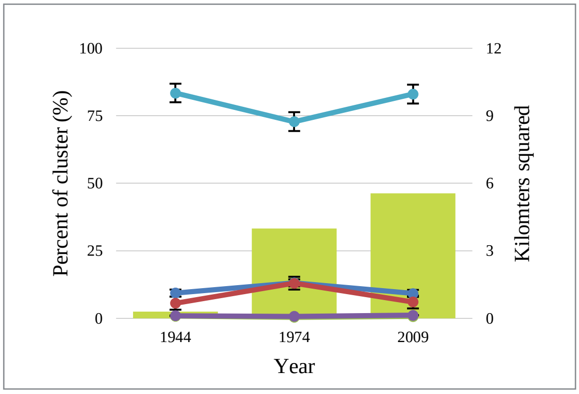
(a) Thorndale (northern site)



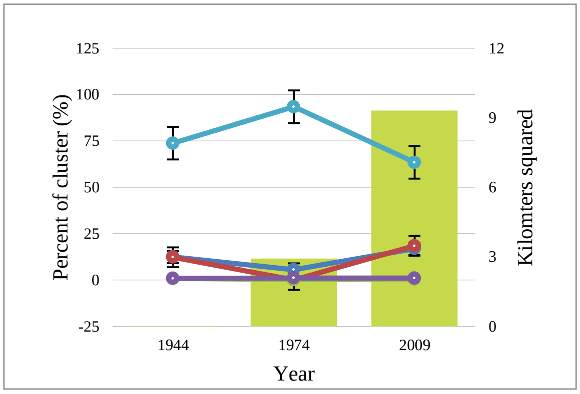
(b) Athol (northern site)



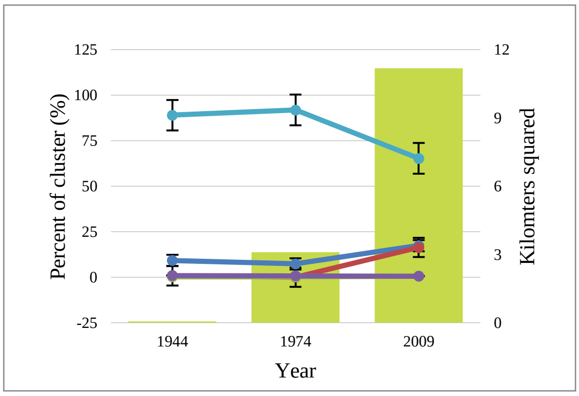
(c) Acornhoek (northern site)



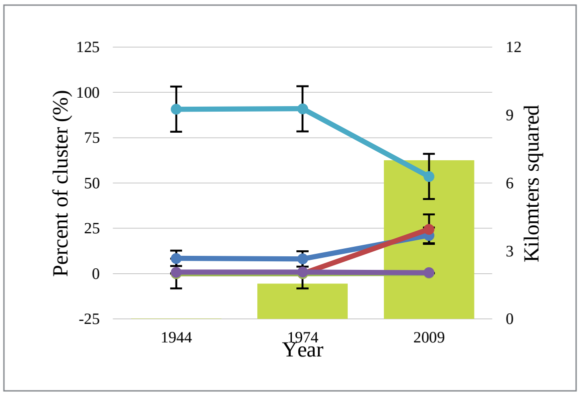
(d) Agincourt 1 (northern site)



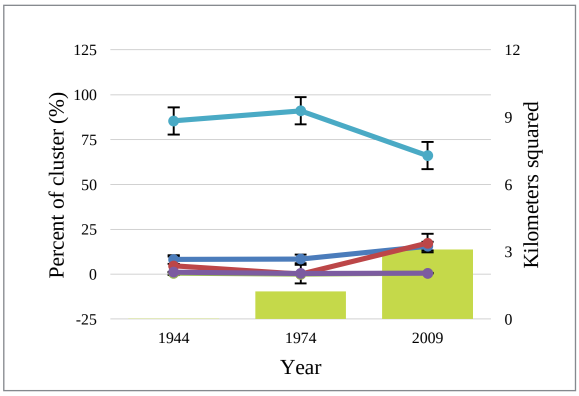
(e) Agincourt 8 (southern site)



(f) Agincourt 9 (southern site)



(g) Agincourt 12 (southern site)

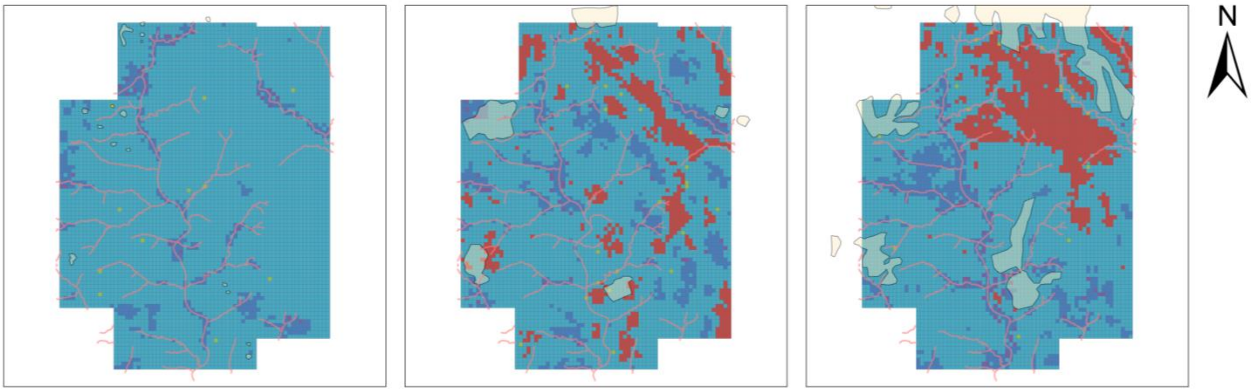


Legend

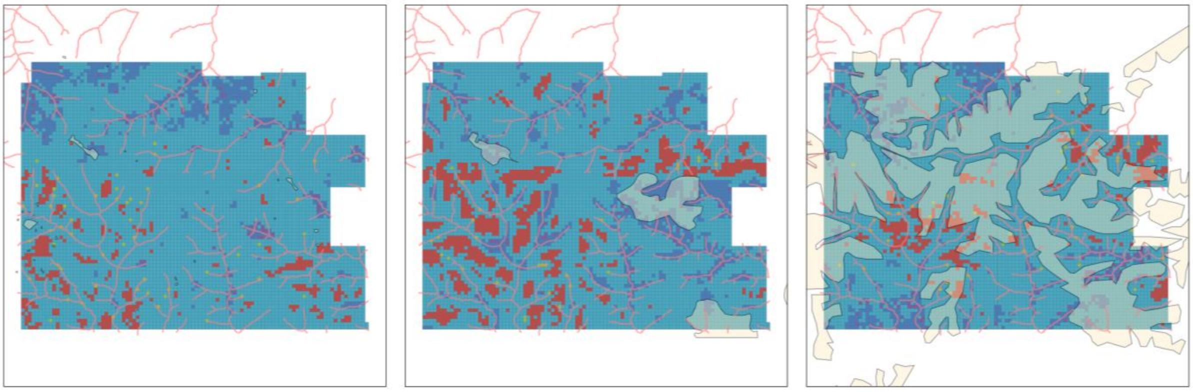
- ○ Clustering of high percentage trees (Hot Spots)
- ○ Clustering of low percentage trees (Cold Spots)
- ○ Outliers - High clustering cell surrounded by low clustering cell
- ○ Outliers - Low clustering cell surrounded by high clustering cell
- ○ Cells of no significant cluster
- 🟩 Village Areas (km²)

2.8.3 Appendix C: Woody canopy cover clustering and village area for individual sites

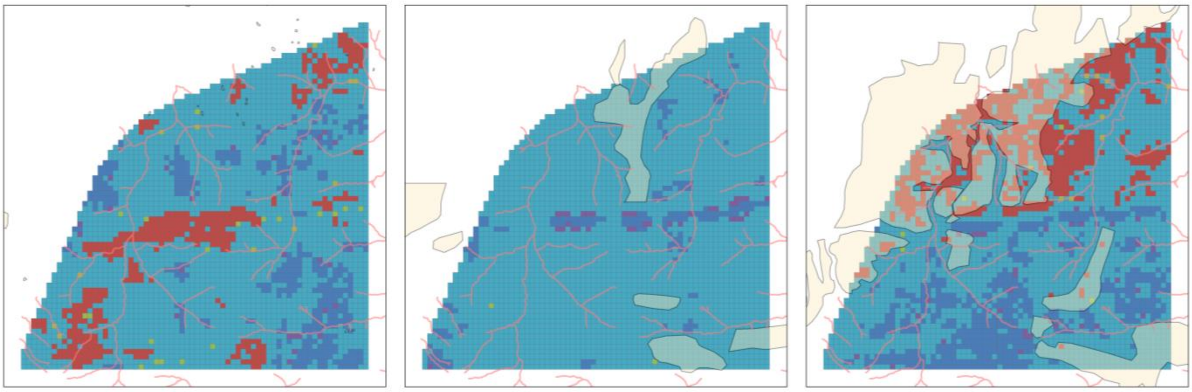
(a) Athol, 1944 (b) Athol, 1974 (c) Athol, 2009



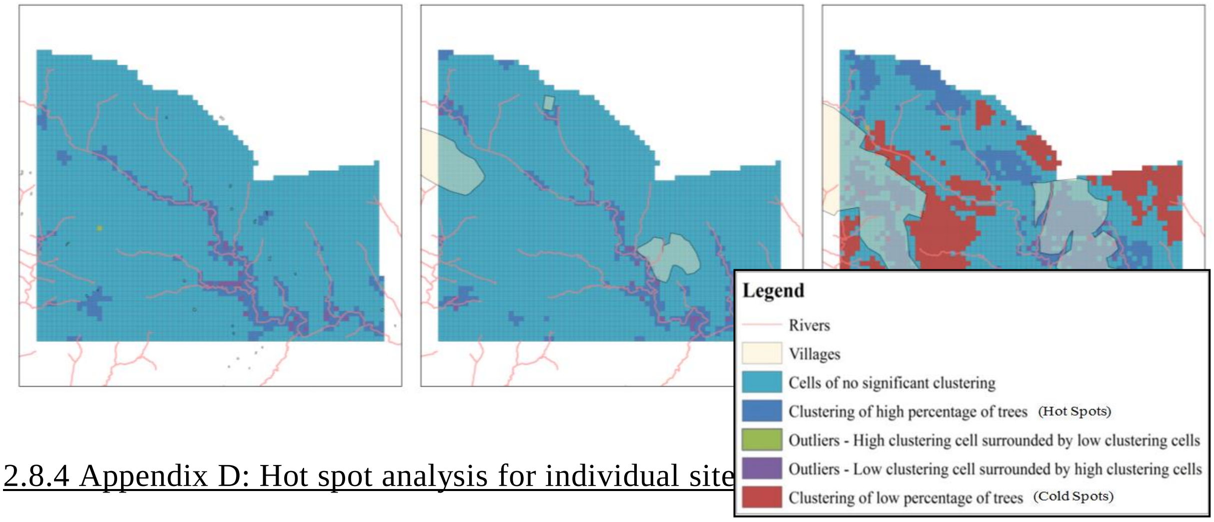
(d) Acornhoek, 1944 (e) Acornhoek, 1974 (f) Acornhoek, 2009



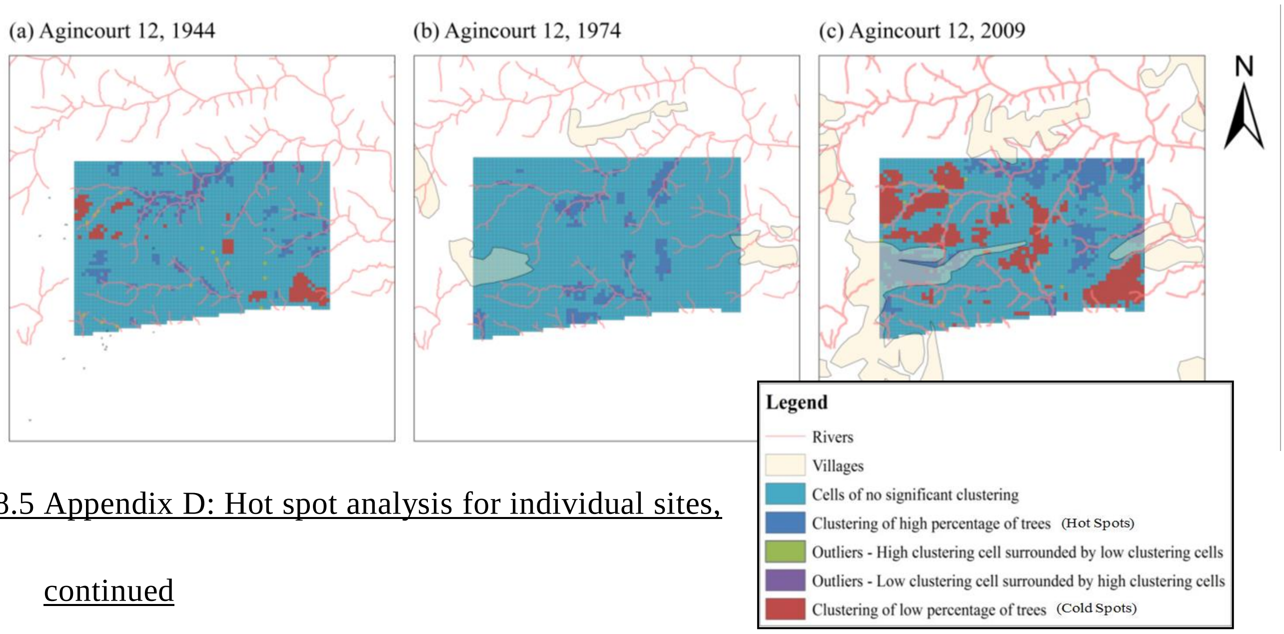
(g) Agincourt 1, 1944 (h) Agincourt 1, 1974 (i) Agincourt 1, 2009



(j) Agincourt 9, 1944 (k) Agincourt 9, 1974 (l) Agincourt 9, 2009



2.8.4 Appendix D: Hot spot analysis for individual site



2.8.5 Appendix D: Hot spot analysis for individual sites, continued

3. Drivers of woody vegetation canopy cover: findings from a long term spatio-temporal study in a communal rangeland savanna

3.1. Abstract

Savanna ecology, and drivers of woody vegetation in particular, have received much attention in research, but few studies have been done both over a significantly long period of time and spatial extent. The rural communal rangelands of South Africa presented an area appropriate for such a study, and we mapped woody cover in 31 995 ha of land over a 65 year period using historical aerial photography data. Our study site was Bushbuckridge in Mpumalanga province, South Africa. Just over half a million people rely on this land for a multitude of environmental services, many of which are provided by the woody plants. Tree canopy coverage was extracted from the data, and this was analysed against five potential drivers of woody canopy cover (geology, mean annual precipitation, relative elevation, distance from river and distance from settlement). Mean annual precipitation (MAP) was the most important driver of woody canopy cover at all points in time (1944, 1974 and 2009), while geology was the least important driver at all the time measurements. An analysis of clusters of woody canopy cover revealed that the abundance of woody canopy cover is not uniform across the spectrum of the drivers' respective values (e.g. canopy cover had a different trajectory over the 65 years in areas of low precipitation compared to areas of high precipitation). We believe that these results may help in monitoring current and future trends in woody canopy cover as they serve as a baseline for future study.

3.2. Introduction

There is a need for a long term spatio-temporal analysis of the change in density and structure of woody vegetation in rural savannas, since 90% of rural household in South Africa use fuelwood, and 30% don't have grid electricity (Shackleton *et al.*, 2007) leading to a massive impact on the environment from the harvesting fuelwood. The former *bantustan* area of Bushbuckridge (BBR) in South Africa is typical of this fuelwood-driven energy system. A large proportion of BBR is communal rangeland. In classical rangeland theory, communal rangeland management of natural resources is seen as unsustainable and unproductive (Abel, 1993 in Parson *et al.*, 1997). Other research, however, points to the conclusion that it may be otherwise (Parsons et al., 1997, Giannecchini et al., 2007). Since the first democratic election in South Africa in 1994, there has been a strong sense of the weakening and marginalisation of the traditional authorities, who had control over natural resources (Twine, 2005; Giannecchini *et al*., 2007). Governance is now unclear as tensions emerge between traditional authorities and newly formed democratic institutions (Dovie *et al.*, 2004). The most striking example is the cutting of live wood from trees, which is banned under traditional law, but is practiced openly today (Dovie, *et al*., 2004; Twine, 2005; Giannecchini *et al.*, 2007). Another example is the trading and commercialisation of *marula* fruit products, particularly beer, which was not practiced in the past due to its sale being prohibited by customary taboos (Shackleton, 2004). Outsiders are increasingly harvesting in the areas around villages because of the changes in institutional control, especially since the 1994 democratic freedom (Twine, 2005; Giannecchini *et al.*, 2007; Grainger, 2009) and because of an increase in unemployment (Twine, 2005).

Within the former-*bantustan* areas, a number of drivers operate to determine vegetation density. While the aforementioned anthropogenic factors are important, a number of biophysical factors may also contribute to determination of vegetation density. Wessels *et al.* (2011) found geological types (gabbro and granite substrates) to be the overriding factor influencing the impact of communal land use on woody vegetation, while Fisher *et al.* (2011) found geology not be a factor in determining vegetation structure at finer scales of investigation but landscape position to be important at these scales. Other abiotic factors that Fisher *et al.* (2011) found to be significant include distance to villages, distance to roads and relative elevation from a river channel. Levick & Rogers (2011) found, albeit in a natural reserve, that landscape position is crucial to understanding drivers that operate in determining woody canopy cover. Scholes (1997) describes a catena as a topo-sequence of soils and vegetation established by the migration of fine soil particles and ions from ridges to valley floors under the influence of gravity and the movement of water. This may be at a scale of meters to kilometers. Soil moisture, and its availability to plants, is determined by the soil type (in terms of clay content). This difference in soils (as a sequence along a slope gradient) is reflected in plant productivity (Cronje *et al.*, 2008). On granite broad-leaved savanna species occur on the upper mid-slopes and toplands, and fine-leaved savanna species occur on the lower mid-slopes and bottomlands (Scholes, 1997). On basalt substrates, there is a linear plant-biomass relationship, with the highest biomass near the streams at the valley bottom, decreasing linearly towards the crests (Colgan *et al.*, 2008). The position on a catena is significant in determining vegetation structure in communal South African savannas (Fisher *et al.*, 2011). Although communal lands have been shown to be resilient to anthropogenic disturbances (Shackleton, 1993b; Harrison & Shackleton, 1999; Giannecchini *et al.*, 2007), Higgins *et al.* (1999) found that toplands and bottomlands respond differently to resource use regimes, possibly because toplands are utilised more for harvesting or because toplands are less resilient to management. This may also be due to the aforementioned differences in the species compositions.

Due to the impact of human activities, it is reasonable to expect that anthropogenic drivers will be important, if not the most important, drivers throughout the entire study period, with their relative influence increasing through time as human population increased. Rainfall and geology should have a constant impact as drivers of woody canopy cover, since they are contributing factors to the general functioning of plants. We expect a shift in importance of these biophysical factors, from being the most important during the early time period in the study, to being less important than the anthropogenic factors at the later time periods of the study. If there is such a shift, it will indicate that the processes that drive certain aspects of the landscape are influenced by human activities, and the landscape may undergo more rapid changes than if there were no anthropogenic drivers influencing it. However, if no such shift is detected it may mean that while anthropogenic drivers are influencing the landscape, the biophysical drivers are still the underpinning factors for determining the landscape, and that there is probably an interplay between these two groups of drivers. The presence or absence of a shift may lead to a more holistic understanding of how landscapes change and adapt under anthropogenic disturbances.

Although previous research has addressed the issues of long term spatio-temporal analysis of the change in density and structure of woody vegetation in rural savannas (e.g. Levick & Rogers, 2011, Fisher *et al.*, 2011), none have done so over a long period of time *and* for a large enough area to grasp changes, and their drivers, at a landscape level. The purpose of this chapter is to determine the relative contributions of a selection of drivers over time, so that we better understand how landscapes evolve. We used Object Based Image Analysis (OBIA) to quantify woody tree canopy cover, and random forest decision trees as a statistical tool to determine a ranking of importance of five drivers for woody tree canopy cover.

Our first objective was to determine which drivers are important in determining woody canopy covering 31 995 ha of what is now a communal rangeland, over a 65 year period. By determining which drivers are the most important at three points in time (1944, 1974 and 2009), we aimed to explain the changes in woody canopy cover in terms of the selected drivers. This was done by statistically analysing potential drivers of woody canopy cover (geology, Mean Annual Precipitation, relative elevation, distance from river and distance from settlement) at a hectare level, to determine which drivers are the most important in determining woody canopy cover. Biophysical factors are expected to be the most important drivers of woody canopy cover in the first half of the study period, and anthropogenic drivers the most important drivers in the second half of the study period. Our second objective was to determine if the spatial patterns of woody canopy cover are uniform at different values of the drivers. This will help uncover whether spatial patterns of woody canopy cover may be present due to interactions between drivers. We expect that areas of low rainfall will show a large change in the patterns of woody canopy cover, because the low rainfall will mean that the woody vegetation is less robust and more susceptible (meaning that it may perish more frequently) to other disturbances. We also expect a similar outcome in the topographical spatial distribution of woody canopy cover in that low areas (as represented here in low values for relative elevation), which are close to a river channel, may be more robust and show less change in the spatial patterns of woody canopy cover.

3.3 Methods

3.3.1 Study area

This study was conducted in Bushbuckridge (BBR) Mpumalanga Province, South Africa (Figure 3.1). Seven sites were selected, following a classification accuracy assessment (chapter 2). Of the sites selected, three were based on prominent local villages and towns and the areas surrounding them (Thorndale, Athol, and Acornhoek), and four were based on villages that are part of the SUCSES (Sustainability in Socio-Ecological Systems) study. The SUCSES study looks at the ecological consequences of the interactions between humans and the environment, and sites were chosen to match sites in that study in order to compare data.

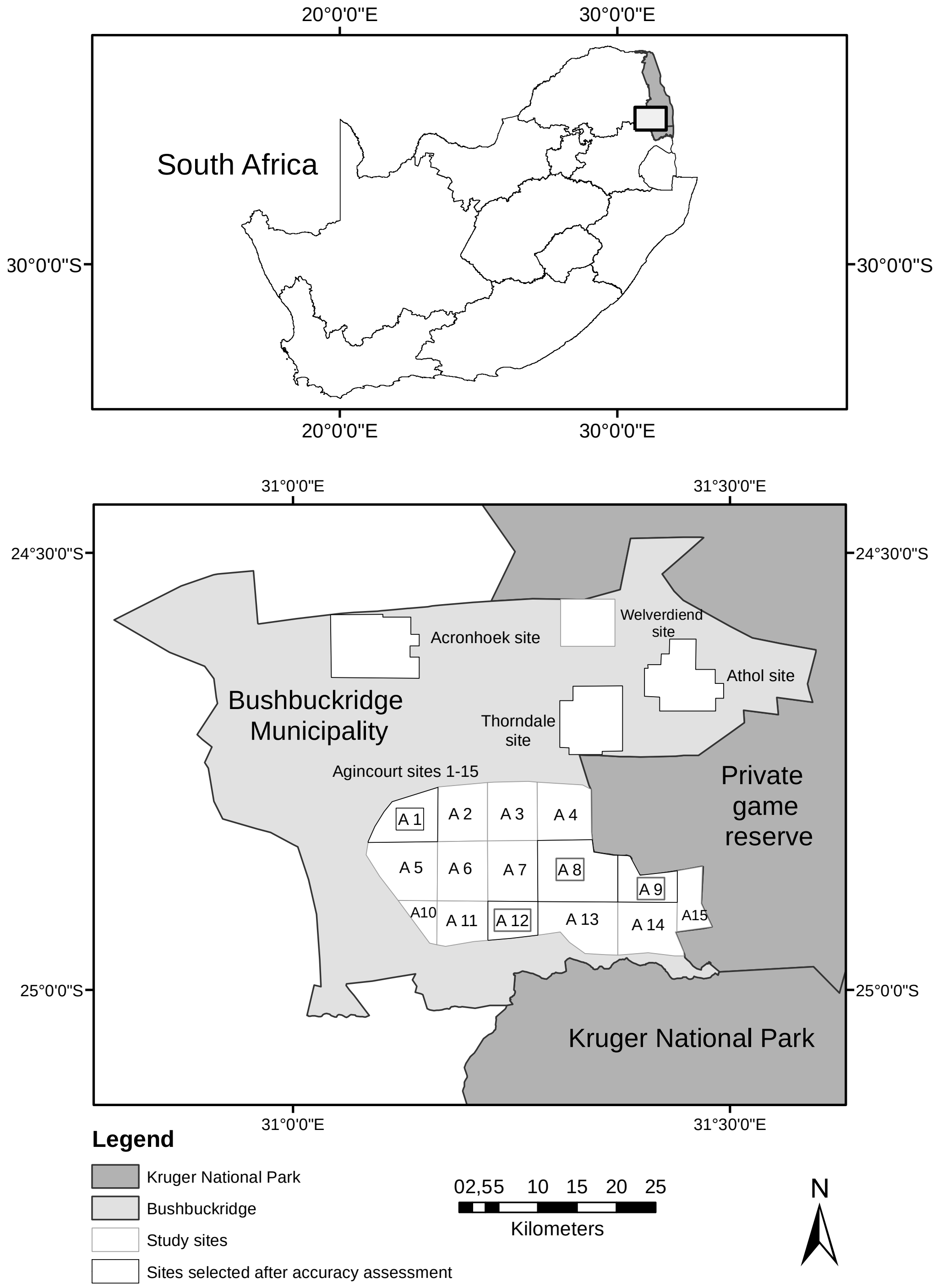


Figure 3.1: The location of Bushbuckridge, South Africa, showing the sites selected following the accuracy assessment in chapter 2 with hatching.

BBR has a distinct east to west gradient in climate, topography and former political boundaries, leading to distinct land-use zones. Changes in the political situation in the country have led to forced relocations of people to BBR in 1959 (Promotion of Bantu Self-government Act, 1959). This, coupled with the arrival of refugees from Mozambique in the 1980s (Shackleton, 2000), who became naturalized citizens because they are of the same ethnic group as the locals (Gianecchini *et* *al.*, 2007), and the AIDS epidemic, has meant that the population of BBR has changed dramatically in the last century. The villages have grown exponentially, and the accompanying infrastructure, such as the road network, has also grown to accommodate this. The highest density of villages is in the centre of BBR, which is communal rangeland.

The mean annual rainfall in the west is 1200mm and in the drier east it is 550mm and the mean annual temperature is 22° C. The topography of the area is generally flat and undulating, and it has underlying granodiorite and potassic granites. The soils consist of sandy lithosols, but deeper duplex soils are more common towards the base of the catena and close to the Drakensburg escarpment in the west, where deep, apedal soils are present (Shackleton, 1993b; Acocks, 1988). (Acocks,1988). To the east of BBR the primary land use is commercial forestry, and to the east private and national game reserves.

3.3.2 Data sources

The data on woody canopy coverage are that derived from the imagery in Chapter 2. These data consist of woody canopy cover at a hectare level for three years: 1944, 1974 and 2009, selected because they represent the era before the *Apartheid bantustan* system was implemented (1944), after it was implemented and a major influx of Mozambican refugees (1974), and after democratic change (2009). In chapter two object based image analysis (OBIA) was used to estimate tree canopy cover. Object based image analysis (OBIA) is a relatively new approach to image classification. It employs the use of an algorithm that groups pixels in an image into objects (segmentation), and then uses the properties of the objects for classification. These properties include contextual reasoning (small round objects surrounded by larger homogenous areas are tree canopies), texture, size, shape, as well as the grouped pixel properties of each object (such as mean brightness of a specific pixel band). OBIA has been shown to be ideal for vegetation analysis, and has recently been used (Laliberte, 2004; Levick & Rogers, 2011; Fisher *et al*., 2013). The hot spot analysis data from chapter two are also used in his study.

The following data of potential drivers for tree canopy cover were collected for the study sites; Geology (1:250 000 South African National set, vectorised digital data); long term mean annual precipitation (MAP) (Schulze *et al.,* 2008) and a Digital Elevation Model (DEM) (The source of the DEM data was SRTM (Shuttle Radar Topography Mission) (USGS, 2004). The MAP provided by Shulze *et al.,* 2008 was from a dataset for South Africa collected from over 9500 rainfall stations with at least 15 years of monthly data (Dent *et al.,* 1989). The DEM was used to create a relative elevation model which was used to determine the elevation of a point in relation to its surroundings, and was used to determine the distance above a river channel; important here as this may influence vegetation. In order to create this model, the DEM was input into the Land Facet Corridor Designer (using the standardised elevation option for the TPI type parameter, with a cell radius of 10) in ArcGIS in order to create a standardised elevation Topographic Position Index (TPI) (Jennes *et al.*, 2011). The output units of the standardised elevation TPI is in standardised deviations used to calculate data on relative elevation (a value of 1 means that the cell is one standard deviation higher than the average elevation of the neighbourhood). These data for all the potential drivers were clipped to the study sites' boundaries in ArcGIS. The boundaries of the settlements and the rivers were manually demarcated in ArcGIS. The calculate areas tool was used to measure village area data for each site. New ArcGis hectare polygon files were created, for each of the sites for each year, containing the distance from the closest settlement and distance from the closest river, using the Euclidean Distance tool in ArcGis.

3.3.3 Analysis

Analysis was performed on the data at a hectare level. The data on tree canopy cover from chapter two contain the amount of woody canopy cover per hectare. All the data analyses were conducted at this resolution.

3.3.4 Explanatory variables

The five sets of data on potential drivers of woody canopy cover were converted from spatial data to numerical data by exporting the grid of hectare cells created in chapter two and exporting the data as a function of each hectare block (using zonal statistics in ArcGis). These data were imported into Excel, where they were analysed and exported in the correct formats for use in other appropriate software packages, as outlined below.

For the second part of the analysis, whereby the spatial relationship between woody canopy cover and the drivers was analysed, the data were further processed as follows. The five variables that relate to the drivers for change (geology, MAP, relative elevation, distance from river and distance from village) were converted into four categories, based on natural breaks (Jenks). Our data on MAP have been divided into categories based on Sankaran *et al.* (2005), who delineates up to 650mm as a 'stable' category, 650 - 780mm as a transition category, and above that an 'unstable' category. A break was manually entered for the distance from village data at 1 kilometre because this was found to be a breakpoint after Wessels *et al. (*2013) who found a decline in harvesting due to fewer people willing to walk further than this point to harvest. The relative elevation data were divided into four categories of relative elevation, which represent catenal position.. The four categories can be considered lowlands (-2.66 to -0.63 standard deviations), gentle slopes (-0.63 to 0.04 standard deviations), flatlands (0.04 to 0.68 standard deviations) and highlands (0.68 to 3.89 standard deviations). The geology data were kept in the two categories (granite and gabbro) as these are the two main geological types in the area. The distance form river data were not altered and the natural beaks (Jenks) categories used.

3.3.4.1 Methodology in determining the relative importance of drivers of woody canopy cover

The importance of the five potential drivers of woody canopy cover was statistically determined using random forest decision trees. This method involves an ensemble of regression trees which is random in two ways: firstly it selects a random subsample of the data to calculate the regression trees, and secondly this is done using a randomly selected and restricted subset of predictors for each split in each tree. This results in random forests being better able to determine the behaviour and contribution of each predictor than simpler mixed effect or regression models, both singularly and with interactions (Strobl *et al.,* 2009a). The data in Excel were saved as a comma separated value file (.csv) and imported into the R statistical software programme, version 3.1.0 (R Foundation for Statistical Computing, Vienna, Austria). The "party" package (Hothorn *et al.*, 2006) was installed, loaded and used to perform random forest statistical analyses on the data, separately for the 1944, 1974 and 2009 data. This analysis ascertains which of the drivers are best at explaining the woody canopy cover, and ranks them in order of their importance.

The forests were run with the geology data set as a factor, and parameter settings (tree = 500 and *mtry* = 3 - mtry indicates how many predictors should be considered for each split of the tree, and is generally set to the square root of the number of predictor variables) as suggested by Strobl *et al.,* (2009b). The *cforest_unbiased* controls (a set of parameters specified to be used by the user) are used as they ensure an unbiased random forest is run (Horthron *et al.*, 2006). A random integer between one and 500 was generated and set as the seed. A random forest was then run on the data using the *cforest* function in R. The same seed was again set and the variable importance of the predictor variables function was calculated using the *varimp* function. This was repeated ten times for each of the three measurements. Repetition is necessary to ensure that the results are stable and robust, and not hindered by a bad seed (Strobl *et al.,* 2009a).

3.3.4.2 Spatial relationship between woody canopy cover and potential drivers of woody canopy cover

The data of the five variables prepared into categories, as outlined above, were used to generate information on which classes of the hot spot analysis (hot spots, cold spots, non-significant areas and outliers) are found in each of the classes for each variable. As such, the outcome through time of the hot spot analysis could be tracked in terms of the categories of the drivers. For example, the areas of high rainfall could be compared to see how the ratio (the five classes were made into ratios so that the percentage of each class was shown and made up 100% of coverage) of hot spot classes changed through time, to analyse whether the areas where high rainfall occurred are more or less prone to change in the spatial patterns of the woody canopy cover. This was done for all of the drivers. The cluster and outlier analysis (Anselin Local Morans I) (Anselin, 1995) performed in chapter 2 on the data pertaining to hectare cells of woody canopy cover were used here. These clusterings refer to hectare cells that have been deemed, statistically, “hot spots” (cells of similarly high woody canopy cover), “cold spots” (cells of similarly low woody canopy cover), two types of spatial outliers (a high woody canopy cover cell surrounded by low woody canopy cover cells, and a low woody canopy cover cell surrounded by high woody canopy cover cells) and clusters of non-significant cells. The clusters are determined by the focal cell being compared to its neighbour and then assigned a value based on statistical significance (0.05 p-value) which indicates whether the null hypothesis of Complete Spatial Randomness (CSR) can be rejected or not.. It is therefore a relative measure. The “zonal statistics as a table tool” was used to determine statistics for each of the hectare cells for each driver. These data were imported into Excel 2010 and graphed for interpretation. These data were compared to the clusters analysis, and data recorded as to which clusters occupy the different zones of drivers.

3.4. Results

3.4.1 Drivers of woody canopy cover

MAP was the most important of the five drivers of tree canopy cover throughout the study period, while geology was the least important (Figures 3.2 a through c). In 1944, the second most important driver was the distance from village, followed by relative elevation, distance from river, and geology (Figure 3.2 a).

In 1974, the most important drivers were MAP, distance from river, relative elevation, distance from village and geology, respectively (Figure 3.2 b). 2009 differs from the other two years of study in that relative elevation is the second most important driver of canopy cover, followed by distance from river, distance from village and finally geology (Figure 3.2 c). It is important to note that the values for relative importance (on the x-axis of Figures 3.2 a through c) are not absolute values that can be compared between studies, but relative ranking of significant predictors (Strobl *et al.*, 2009a). The value of each predictor changes within each run of the data as the random seed is changed, so the value assigned on the x axis has no value, only the order in which they are ranked. This is due to the random nature of random forest models, and therefore only the ranking of the variables should be taken into consideration. There were no changes in the rankings of the variables over the multiple runs of the random forests and Figure 3.2 (a) through (c) are, therefore, representative of any and all of the iterations.

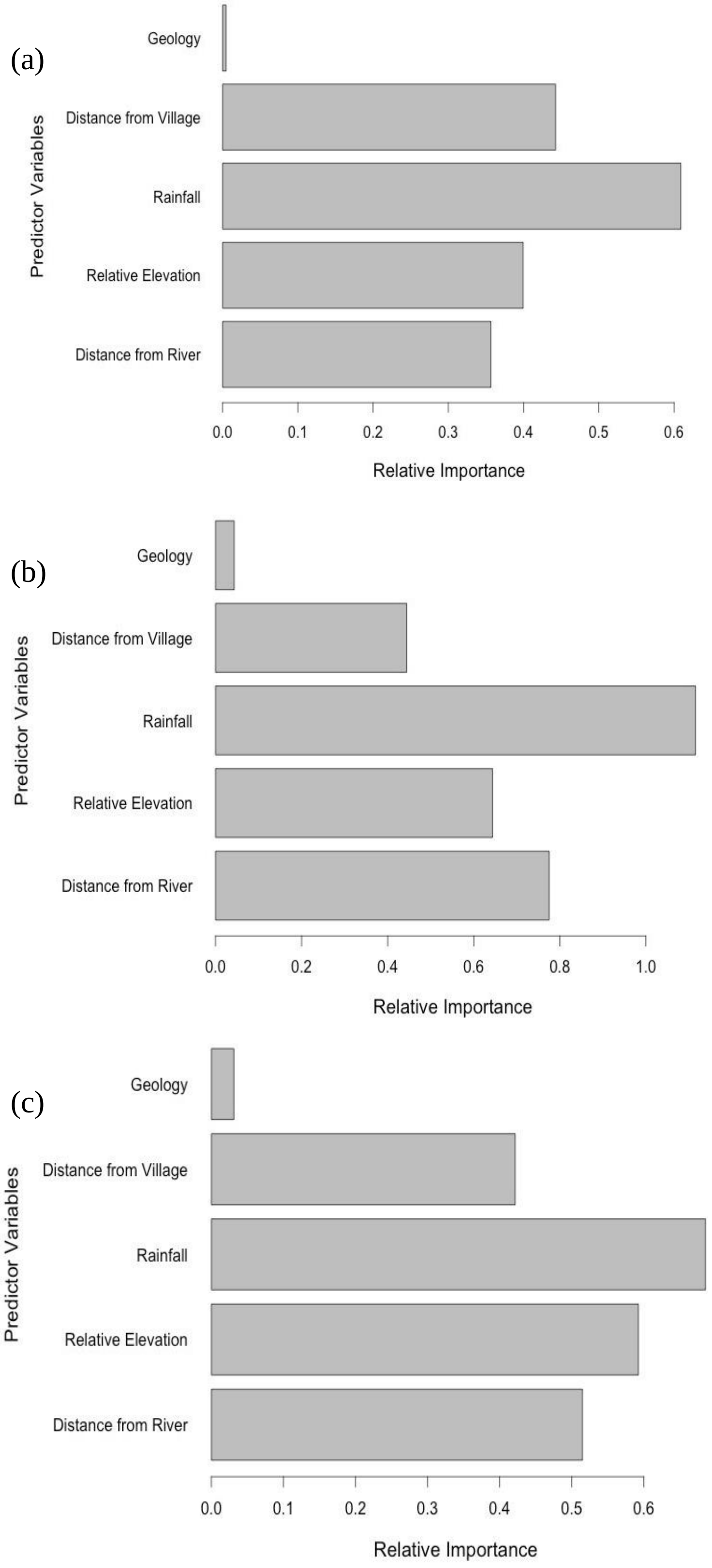


Figure 3.2: Relative importance of drivers of woody canopy cover in (a) 1944, (b) 1974 and (c) 2009.

3.4.2 Drivers of woody canopy cover and their relation to the hot spot analysis of woody canopy cover

The lowest rainfall category (546 to 670mm) had the highest change, with both the hot spots and cold spots of woody canopy cover increasing from 9% to 18% and 1% to 18% over the entire study period, respectively. The highest rainfall category (945mm to 1171mm) showed a decrease in cold spots and an increase in hot spots resulting in a shift in the ratio of those two, with the ratio of cold to hot spots decreasing from 1944 to 2009. The two categories of rainfall in-between the two extremities (670mm to 788mm and 788mm to 945mm) showed an overall increase of both hot and cold spots (Figure 3.3). There is a distinct difference in the changes in cells of hot spots among the categories. In the first category there is an increase in both hot and cold spots at the expense of non-significant cells throughout the study period, while the second sees an increase between 1944 and 1974, and then little change in 2009. The third category shows an initial decrease and then an increase, while the last category has a decrease and then slight increase in hot and cold spots. .

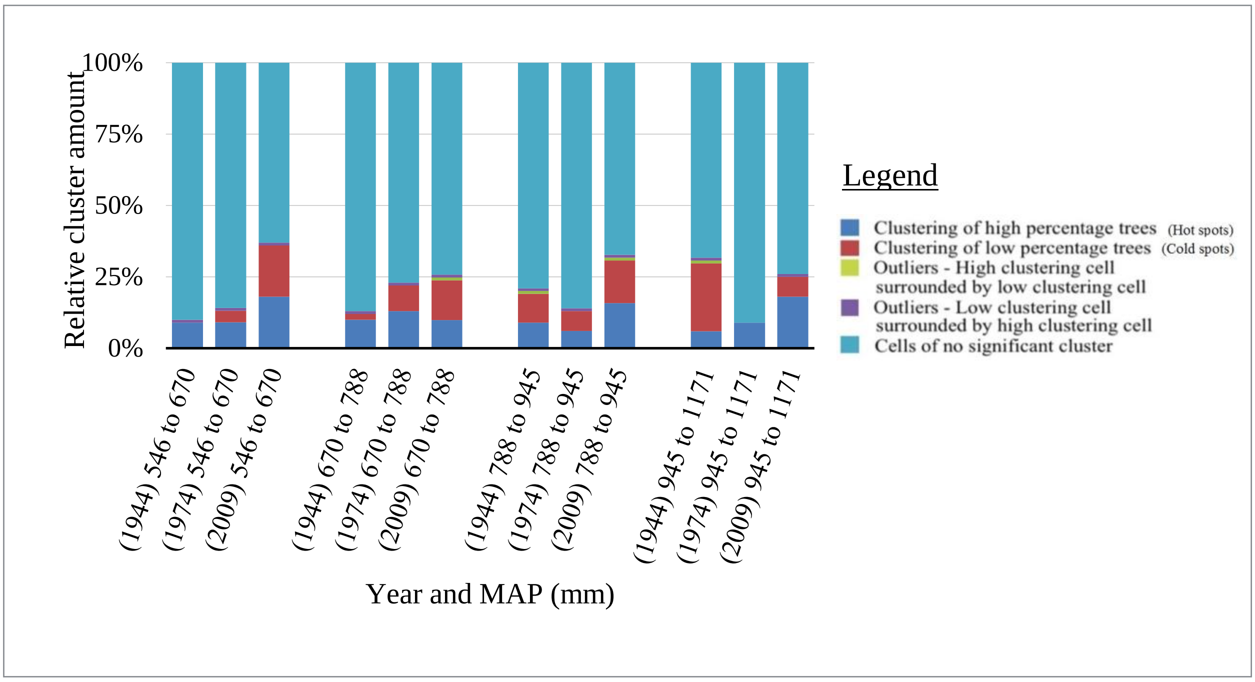


Figure 3.3: Relative amount of cluster in each of the four MAP categories

While all categories of relative elevation show a marked increase in hot and cold spots, lowlands (the -2.66 to -0.63 standard deviations category) are different in that they show an increase in cold spots at the expense of hot spots and non-significant cells. The other three categories of relative elevation (representing gentle slopes, flatlands and highlands) show a much greater shift in increase of hot and cold spots, at the expense of non-significant cells only (Figure 3.4). The bottomlands show a slight decrease in hot spots through time, while all three other categories had an almost identical growth in hot and cold spots from 1944 to 2009.

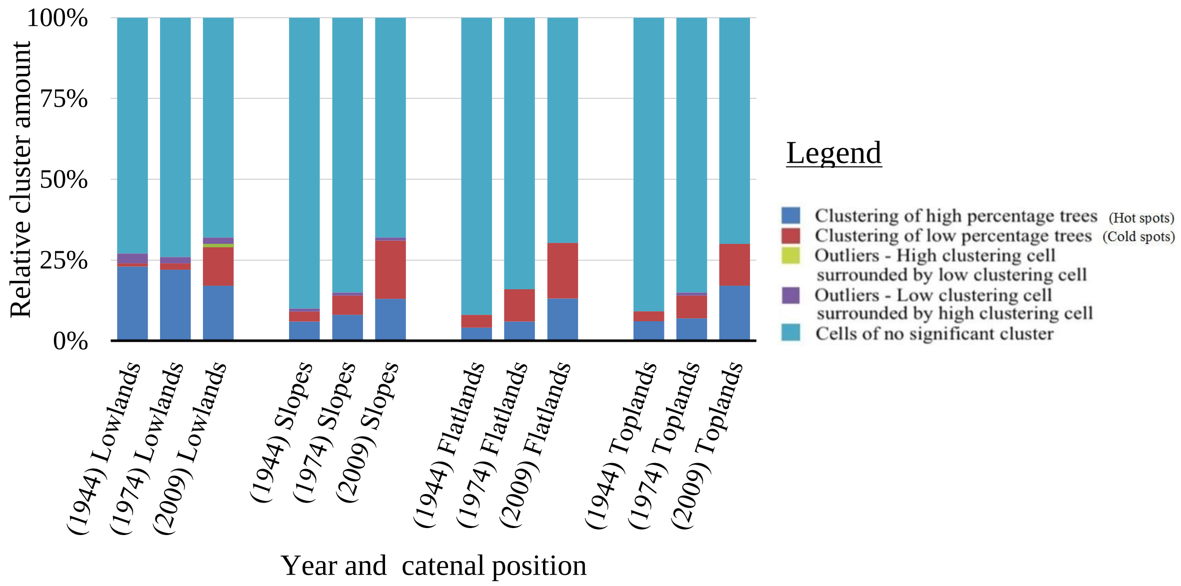


Figure 3.4: Relative amount of cluster in each of the four relative elevation categories

The category closest to the river had a stable amount of hot spots over the study period, while the three further categories had a marked increase in the amount of hot spots (Figure 3.5). The three categories closest to the river showed a large increase in cold spots, while the category furthest from the river showed only a very small increase in cold spots. This category furthest from the river (1171 to 2552 metres) has the largest increases in significant clustering, going from 0% in 1944 to 21% in 2009 for both hot and cold spots combined.

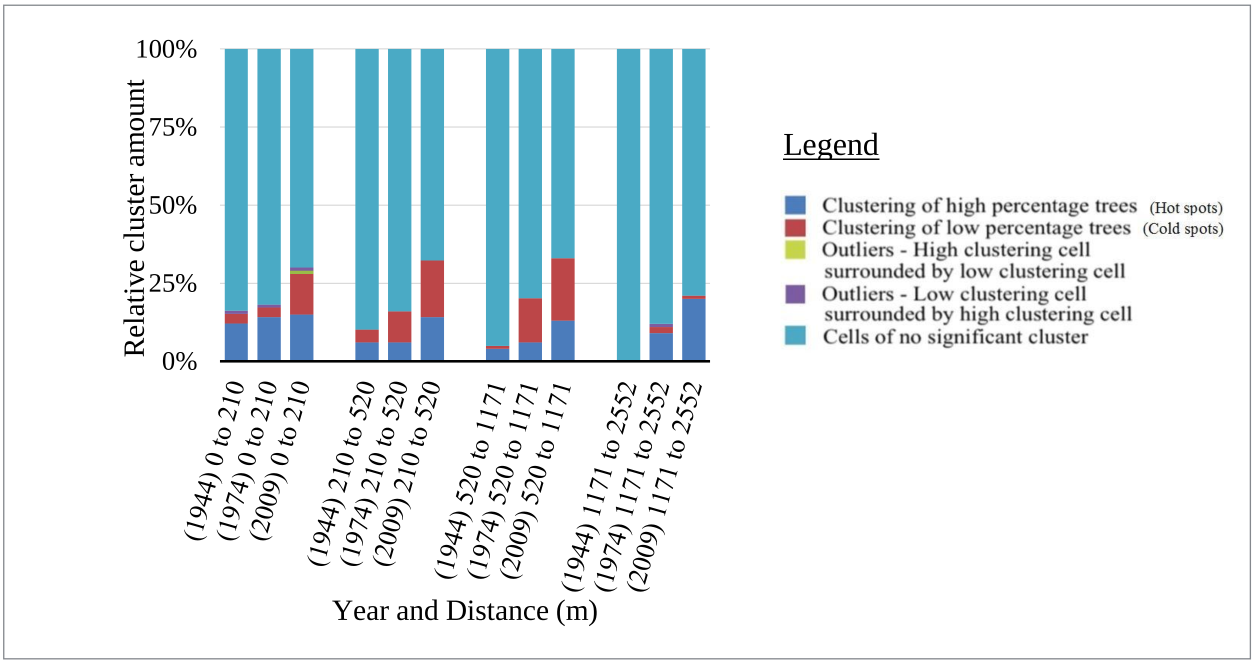


Figure 3.5: Relative amount of cluster in each of the four distances from river categories

While the three categories closest to villages all had an increase in combined hot and cold spots, the furthest category (3451m to 6985m) had the largest increase in hot and cold spots, mainly driven by a large increase in hot spots (Figure 3.6). All four categories showed a similar trend in the increase of hot and cold spots through time. In terms of cells of hot spots, the first 1000m increased from 10% to 12% (20% increase), 1000m-1863m saw a 10% to 14% (40% increase), 1863m-3451m from 5% to 17% (240% increase) and 3451m-6985m from 9% to 30% (233% increase). There was a decrease in the growth of cold spots moving away from the village; the closest category increased by 433%, while the furthest category increased by 333%.

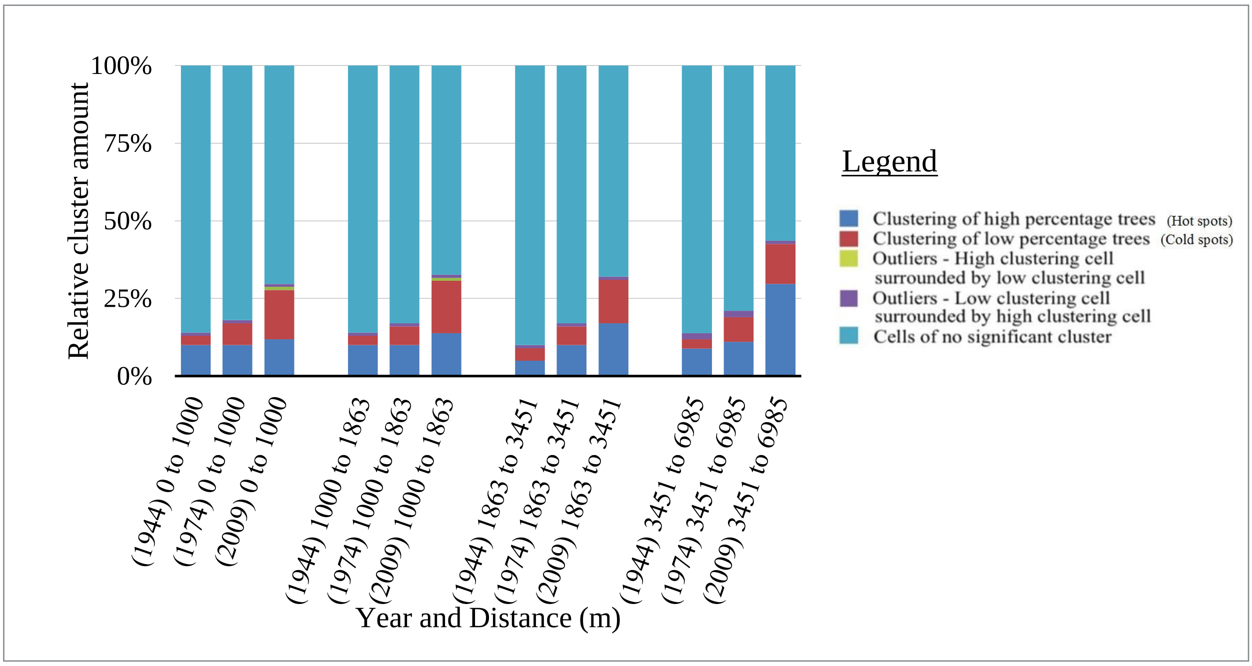


Figure 3.6: Relative amount of cluster in each of the four distances from village categories

An analysis of the effect of underlying geology shows that while both geology types have an increase in hot and cold spots, gabbro is far more heavily impacted than granite landscapes (Figure 3.7). The cold spots in 1944 represent 3% of the total area, and this grew to 33% in 2009, while the granite cold spots grew from 3% in 1944 to 12% in 2009.

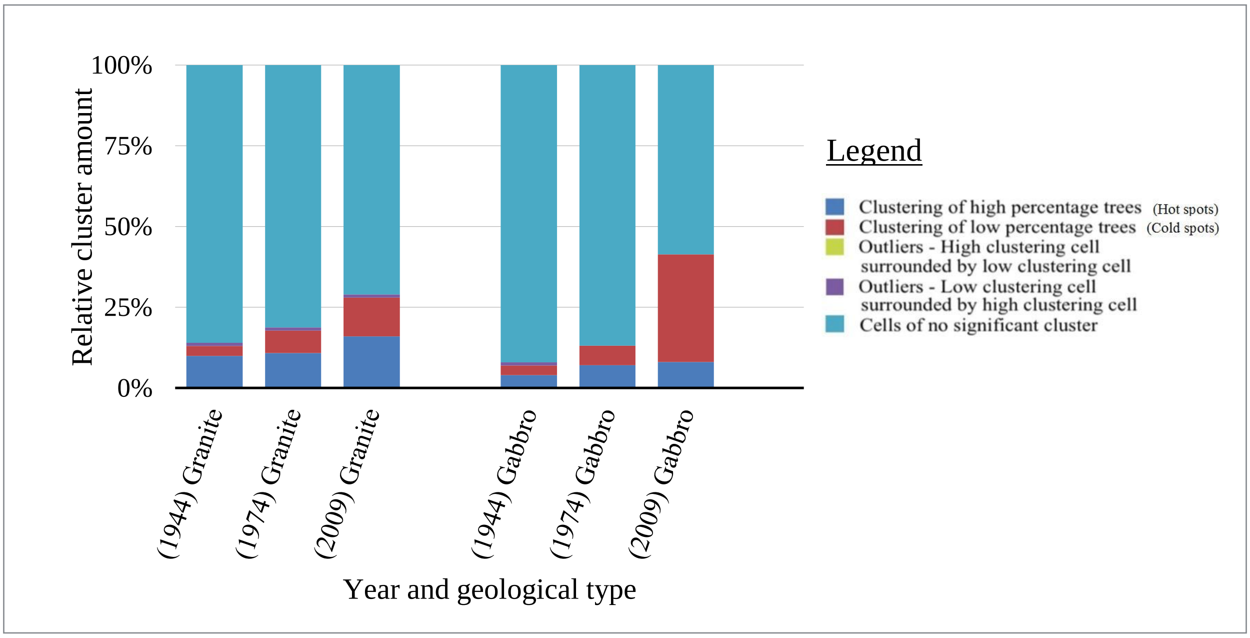


Figure 3.7: Relative amount of cluster in each of the two underlying geology categories

3.5 Discussion

3.5.1 Drivers of woody canopy cover

Some authors have demonstrated that water abundance in a landscape is the main determinant of woody cover in savannas (Walter, 1971; Walker e*t al.*, 1982; Walker & Noy-Meir, 1982). Our data support this, as they show that MAP is the most important driver of canopy cover, of the five drivers selected, throughout the 65 year period. Coughenour & Ellis (1993) found the same when analysing woody cover in 9 000km^2 of savanna in Kenya, when the influence of increased water in riparian zones was eliminated. They proposed that a hierarchy of constraint exists in savannas, with rainfall and hydrology (along with topography) acting at a regional to landscape level. Gillson (2004) proposed that rainfall is the major driver of savanna tree density at the landscape level. At the same time, we found geology to be the least important of all factors, at all three time intervals, which contradicts the findings of Wessels *et al.* (2011) & Wessels *et al.* (2013), but mirrors those of Fisher *et al.* (2011) at a finer scale.

In 1944, the second most important factor after rainfall was distance from the area measured to the closest village. At this time there were very few dwellings in BBR; only homesteads that were isolated and dispersed. Since anthropogenic factors would not have had a large impact on the vegetation at this time, it is likely that people settled close to areas that had large trees (for shelter and resources the trees offered, such as *marul*a fruit), as opposed to their proximity to an area affecting the woody canopy cover in that area. Since this time period represents the least disturbed landscape, it is interesting that after distance from the area under consideration to the closest village (which is extraneous in this situation), relative elevation is most important in determining woody canopy cover. This may be due to the climate differences between hilltops and valleys playing an important role in sparsely settled landscapes; cooler hilltops with marula trees in sandy soils may be a better place to settle than in the hot and humid valley, even though the clayey soils there are better for agriculture. Fisher *et al.* (2011) also found relative elevation to be an important factor at a finer scale of analysis.

The distance from the area measured to the closest river was the second most import factor after rainfall in 1974. The landscape in 1974 was been highly impacted upon, compared to 1944, and the size of the village in the study areas grew from 15km^2 to 45km^2 (chapter 2). Fisher *et al.* (2011) concluded that the distance from the closest river is a significant explanatory variable of woody cover. Interestingly, the distance from the area measured to the closest village was the second least important variable in 1974. This indicates that there had probably been large changes in the landscape between 1944 and 1974, and the village expansion meant that the initial settlement locations in 1944 did not have as much impact on the importance of the village distance as a driver for woody canopy cover.

Distance from the area measured to the closest village remained as the second least important variable in 2009. This is unsurprising as the villages in 2009 have greatly increased in size, by orders of magnitude, since 1974 and many of them have coalesced. Disturbance gradients have been found around the villages in the area (Chapter 2; Fisher *et al.*, 2011; Wessels *et al.*, 2013). Fisher *et al.* (2011) found that these disturbance gradients do coalesce over time around villages that heavily utilise the landscape. This may be the case here, or perhaps it is because in 2009, trees are harvested by people from other villages, collected and transported by vehicles, collected for trade and accessed via roads (Twine 2003; Twine 2005; Grainger, 2009). This means that the distance to a village is not as much of a factor in the selection of trees to harvest, and therefore on woody canopy cover.

Relative elevation became the second most important variable in determining woody canopy cover in 2009. Levick & Rogers (2011) found that woody cover in in the nearby Kruger National Park, increased in toplands and decreased in bottomlands between 1942 and 2001. This, they illustrate, led to a homogenisation of the woody cover and a change in the size class distribution of woody plants over the catenal sequence. Therefore, it is of great interest that relative elevation is the second most important predictor variable in 2009. It may be that by 2009, the impact on woody canopy cover at different parts of the catena was pronounced enough to lead to relative elevation being a significant determinant of woody canopy cover. It must be noted that the Levick & Rogers (2011) study was undertaken in a nearby area unaffected by anthropogenic drivers as it is in an enclosed nature reserve.

3.5.2 Drivers of change and their relation to the clustering of woody canopy cover

Recent research has found that precipitation in African savannas leads to an upper limit on the amount of woody cover. This is observable, and has a linear relationship, up to 650mm MAP. Savannas constrained by this 650mm MAP are considered ‘stable’ system savannas - whereby precipitation constrains the amount of woody cover. Within this upper bound region, soil properties and disturbances (such as fire and herbivory) interact to reduce the overall woody cover. Up to 780mm MAP was considered a transition zone, while above that an ‘unstable’ system savanna - in that disturbances (fire and herbivory) play a more crucial role in the coexistence of trees and grasses due to canopy closure (Sankaran *et al.*, 2005).

Within the stable zone, we found a linear increase in cells of hot spots and cells of cold spots. The second (transition) category also shows a more steady increase in hot and cold spots, with a slight loss of high clusterings in 2009. The last two categories (unstable) show no apparent trend in their changes in hot and cold spots through time, and this may be because disturbances have a far greater impact on these systems because of their unstable nature. The highest rainfall category (945mm to 1171mm) sees a drastic loss of cold spots, and a simultaneous gain in hot spots. If water is the main determinant of the grass-tree ratio (Walter, 1939 and 1971), then the problem of bush encroachment due to grazing may be accelerated in these high MAP areas. This supports the findings of Sankaran *et al.* (2005) in that the stable zone appears to have a predictable, linear increase in woody canopy cover, whereas the other unstable zones tend to have unpredictable, non-linear changes through time. This suggests that up to the 670mm, precipitation limits the upper bound of woody canopy cover, whereas in areas with higher rainfall, other disturbances have a far greater effect on the woody canopy cover.

The bottomlands tend to have fertile, clay soil, and thus not subject to higher grazing pressure, and hence our finding of a decrease in hot spots in the bottomlands. Since the catenal sequence prescribes different species compositions at the top and bottomlands, the species at the toplands may be able to withstand disturbances (in this case anthropogenic harvesting) to a greater degree than the bottomlands. However, a study in the same area as this study has shown that, of three species studied, two showed a strong capacity for coppicing in bottomlands (Kaschula *et al.*, 2005). Therefore, the observed increase in hot spots on the higher areas is more likely due to bush encroachment.

Since some authors argue that water availability is the chief determinant of woody cover in savannas (Walter, 1939; Walter 1971; Walker *et al.*, 1981; Walker *et al.*, 1982), and riverine bottomlands have been found to have a different vegetation structure (above & Scholes, 1997), the distance from the area measured to the closest river may have an impact on the amount of woody canopy cover present in a landscape. We found that within 210 m from the nearest river, hot spots of woody canopy cover have remained relatively stable over the 65 year study period. From 210 m to 1171 m there has been a larger increase in hot spots over the study period, while 1171 m to 2552 m shows the largest gain in hot spots of woody canopy cover. This may indicate that the riparian areas (which are included in this first rainfall category) may not be harvested as much as in areas further away from rivers, and so the amount of hot spots has remained stable. These areas may not be harvested as much as other areas because preferred species for harvesting, such as *Dichrostachys cinerea* and *Terminalia sericea* (Madubansi & Shackleton, 2007) are generally not found in riparian areas. The large increase in all the other categories may be due to bush encroachment, which would occur on the flatter areas, as mentioned above, and is especially observable in the area furthest from the river (1171m to 2552m). The areas from 210m to 1171m represent the areas where most of the anthropogenic disturbances are likely to occur (within moderate walking distance of the river) and they appropriately show a disturbance in the landscape - manifesting as an increase in both hot and cold spots throughout the 65 year study period.

Studies on woody cover in communal savannas have revealed gradients of disturbances around villages (Shackleton *et al.*, 1994; Banks *et al.*, 1996; Fisher *et al.*, 2011; Wessels *et al.*, 2013). Disturbance gradients were found in this data set, where disturbance was found up to 1000m from villages (chapter 2). The categories we used to split the range of our "distance from village" driver were selected so that they were aligned with these results, as well as those of Wessels *et al.* (2013). Interestingly, within the first 1000m, hot spots of woody canopy cover did not change substantially, while the level of increase rose further away from the village. This, again, may be due to the fact that woody plant encroachment occurs further away from the village areas where the fields are located and harvesting pressure is lower. Woody encroachment would most probably be very intense close to villages, except that this is where harvesting is the most intense, and this counteracts the woody plant encroachment. The increase cold spots appeared to decrease the further away from the village the category was, which may show a slight increase in disturbance in terms of removal of trees. This indicates that the cold spot disturbances are probably from harvesting - which would likely be more uniform throughout the landscape because people harvest wherever a suitable tree is situated. It must be noted that this hot spot analysis does not show the presence or absence of disturbance gradients, as it is not a measure of overall tree canopy cover, and because site specificity is important in disturbance gradients (Fisher *et al.*, 2011) and our data are not site specific.

Geology has been found to be highly influential in determining woody canopy cover (Wessels *et al.*, 2011; Wessels *et al.*, 2013). However, in those studies there was a clear interplay between underlying geology, land use and distance from nearest village. Wessels *et al.* (2011) found that areas with gabbro as the underlying geology had differing responses to communal land use, ranging from a radical reduction to a substantial increase in woody canopy cover. This was reportedly due to the land management regimes, both current and historical. Areas with granite as the underlying geology had a 50% reduction in woody cover due to communal land use. Our data show that areas with granite as the underlying geology had a linear and gradual response to disturbance through the study period. Areas with gabbro as the underlying geology had a drastic increase in cold spots, while the amount of hot spots remained almost the same over the study period. This increase in cold spots may be due to the trees present on gabbro areas being more desirable to harvesters, or gabbro areas having been transformed into fields.

3.6. Conclusion

MAP is the most important driver of woody canopy cover over the 65 year study period, out of the drivers analysed here. This is surprising in that it does not support our original hypothesis that anthropogenic drivers are the most important drivers throughout the study period, and that their importance would increase through time. An analysis of hot spots of woody canopy cover against the same drivers showed that drivers influenced woody canopy cover differently with different magnitudes of their values (such as high vs. low rainfall). Most importantly, MAP of up to 670 mm was shown to lead to a linear, predictable increase in canopy cover through time, while higher rainfall led to a far more unstable trajectory of woody canopy cover. At a landscape scale, MAP was the most important driver of woody canopy cover. However, within different categories of rainfall, the woody canopy cover differed in the changes it experienced in patterns of woody canopy cover through time. Geology, conversely, was the least important driver of woody canopy cover at all time periods in the study. Riparian zones appeared to be the least disturbed areas in this study, retaining their patterns of areas of high woody canopy cover throughout the study. While we acknowledge that we have chosen only a few of the vast amount of drivers that play a role in determining woody canopy cover, they are amongst the few that are readily available for a study of this temporal magnitude. However, these drivers have been investigated in numerous other studies (e.g. Wessels *et al.*, 2011; Levick & Rogers, 2011; Fisher *et al.*, 2011), and are therefore favourable choices as they are comparable.

We have demonstrated that different drivers operate at different scales, both spatially and temporally. Temporally, the second most important driver, after MAP, was different for all three years measured; being the distance from the area measured to the closest village, the distance from the area measured to the closest river and the relative elevation for 1944, 1974 and 2009, respectively. This highlights the importance of a large temporal aspect to a study on drivers of savanna woody canopy cover. Interestingly, the midslopes and toplands all had a similar linear increases in woody canopy cover through time, while the bottomlands had a more stable amount of woody canopy cover through time. This may point to the plant species in the bottommlands being more resilient to forces impacting other areas, or that the abundance of water in these places makes them more resilient.

We think that long term baseline data are essential when conducting a study of this nature, and we hope that our data will provide this. Future research may use the trend in canopy change associated with drivers for change to focus on how short term trends relate to the long term trends presented here. Additionally, management decisions may be better informed by these findings as conservation can be better focused in areas where the long term trends are showing a decline in woody canopy cover, or where long term trends are shifting in the short term.

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4. Synthesis and recommendations

4.1 Introduction

Spatio-temporal analyses of woody vegetation dynamics and their drivers have been undertaken in savannas (Gillson, 2004; Levick & Rogers, 2011; Sankaran *et al.*, 2005; Scholes & Archer, 1997). Some of these were conducted in communal rangelands (e.g. Fisher *et al.*, 2013) because they represent an interesting mix of social and ecological problems. These communal savannas are being transformed due to the local peoples' use of the natural resources as their main energy source (Twine, 2005). Some studies have modelled use patterns and determined that these woody biomass resources should have been depleted by present day (e.g. Banks *et al.*, 1996), but we found that this is not the case when using woody canopy cover as a tool to infer biomass.

The research presented here was necessitated by the need to investigate the dynamics of heavily impacted South African communal savanna systems, as they are relied upon by millions of people in South Africa; over half a million people in BBR alone (Statistics South Africa, 2011). Within this context, historical data are imperative in order to ascertain patterns and trends that occur, since these may happen over timescales that mean they are not easy to detect using relatively recent data. The speed and extent of any change found in woody canopy cover cannot be analysed and compared to what may have occurred in the past studies that do not employ long term data. This is crucial, because without an adequate temporal comparison the relative scale of the change cannot be gauged, because there is nothing to compare it to. In the same manner, certain drivers may operate differently at different time periods, especially anthropogenic ones because the magnitude of their influence may change drastically in a short period of time. Woody canopy cover was selected as the variable used to quantify change that has occurred in the landscape, with regard to extraction of woody biomass. This is because woody canopy cover reflects changes in woody biomass and it is therefore a crude proxy used to indicate the woody biomass, especially from an aerial photographic perspective, which is the only data source available for historical analysis of the temporal magnitude presented here. Coppicing, however, is a problem in this regard, because it can be detected as a tree crown, but the coppicing tree may only be of a low biomass on the ground.

This chapter summarises, synthesises and integrates the finding of chapter two and three. A conceptual model was developed to aid in this purpose. Limitations and recommendations are then discussed.

4.2 Synthesis

Chapter two showed that disturbances in the landscape have occurred as a parallel increase in village size occurred. From the patterns of woody canopy cover seen in this study, it may be that this increase in village size and population has led to an increase in anthropogenic disturbances. These include an increase in livestock grazing (which may lead to bush encroachment, but also leads to an increase in clearing of trees for fields), harvesting (which may have led to a reduction of trees in some areas, but the coppicing of harvested trees may have led to an increase of tree canopy in other areas) and the protection of trees in village yards for food, additional income or cultural reasons (Figure 4.1; left portion of diagram, which represent the findings of chapter 2).

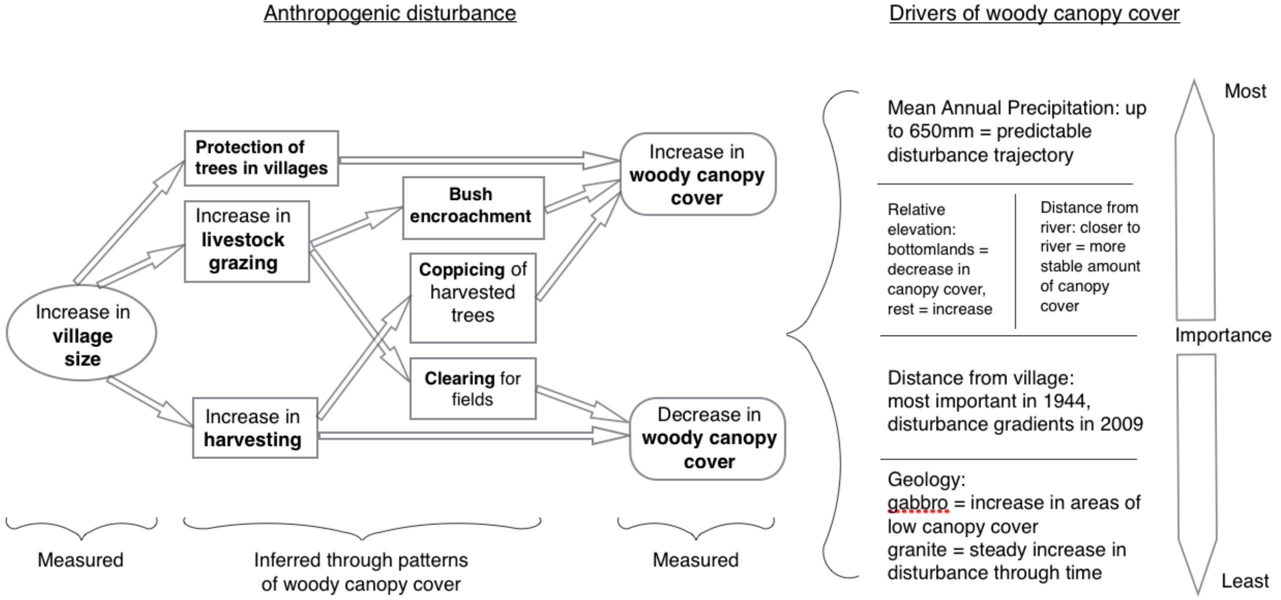

Figure 4.1: Conceptual diagram of the findings in chapter two (left portion of the diagram) and chapter three (right portion of the diagram)

As rural villages expand in the communal savannas, more livestock will be kept and subsequently more land will be used for livestock grazing. Although clearing of woodlands for cropping is common practice for residents as villages expand (Giannecchini *et al.*, 2007), it may not necessarily lead to a net decrease in the observed woody canopy cover at a landscape level. This is due to bush encroachment occurring in overgrazed fields and the cultivation of large fruit-bearing trees in villages. Bush encroachment is a phenomenon whereby there is a drastic increase woody plant biomass, usually in the form of bushes and small trees, at the expense of palatable grasses and herbs (Ward, 2005). Bush encroachment is a problem in South Africa because it affects agricultural productivity and biodiversity (Donaldson, 1980), making it a biodiversity and an agricultural problem (Ward, 2010). The patterns of woody canopy cover in chapter two showed an increase in areas that were previously classified with clusters of significantly low woody canopy cover, through many small canopies that grew and spread. This may represent an area that through overgrazing has led to bush encroachment. Aggregated, these many small woody canopies manifest as areas that are, in the 2009 data, classified as areas of significantly high woody canopy cover. In these areas there is more absolute canopy cover than in 1944, when villages did not exist in the area, and hence livestock grazing was low.

Harvesting of woody resources is well documented in the area (Banks *et al*., 1996; Giannecchini *et al.*, 2007; Matsika *et al*., 2012; Wessels *et al*., 2013) and has not declined over the past three decades, as indicated by a reduction of fuelwood resources around two local villages (Matsika, 2013). However, harvesting of woody resources may not necessarily manifest as an overall decline in woody canopy cover at a landscape. Although in some areas there is a local decline in woody canopy cover, coppicing of felled or harvested trees may have shown as an increase in canopy cover in other areas. Coppicing is a survival mechanism that woody vegetation employs against stem damage that may be caused by fire, herbivory or as a result of trees harvested for fuelwood (Shackleton, 2000). It occurs through the regeneration of damaged stems, and stems damaged through harvesting in savannas have the ability to coppice. Luoga *at al.* (2004) found that a communal, disturbed savanna in Tanzania exhibited virtually the same tree densities as that of an adjacent forest reserve because of coppicing trees. In terms of the methodology employed in this study, it is very probable that much of the woody canopy cover that is detected in the 2009 imagery is actually coppice regrowth, and not a true canopy of a tree.

Since coppicing shoots of harvested trees grow faster than seedlings (Chidumayo, 1993; Grundy *et al.*, 1993), coppicing may be a strategy for producing a sustainable fuelwood source. Coppice regrowth is affected by harvesting techniques (Shackleton, 2000; Kaschula *et al., 2005;* Neke *et al.*, 2006), and Matsikia (2012) found that in a rural communal savanna, stem diameter of harvested coppice regrowth is declining over time. This means that the coppicing mechanism may not be sustainable in the long term. Additionally, if stems are harvested before they reach pole size (4-10cm), few stems become seed-baring trees (Luoga *et al.*, 2004), which has consequences for the genetic diversity of the harvested woody vegetation (Matsikia, 2012). This lack of reaching sexual maturity limits the regeneration ability of these trees through a diminished ability for juvenile recruitment (Fisher *et al.*, 2011).

The protection of large trees in yards is a documented practice in the villages of BBR (Shackleton *et al.*, 2003; Giannecchini *et al.*, 2007; Hunter *et al.*, 2007; Shackleton *et al.*, 2007a). This practice leads to a high density of woody canopies being detected within the rural settlements through aerial observation and analysis of the resultant data (chapter 2). It is likely that these trees are kept and become very large, and may indeed lead to a higher density of woody plant material in villages, than in an undisturbed area.

These three factors combined (an increase in livestock grazing; which may lead to bush encroachment, harvesting; which may lead to coppicing, and the protection of trees in village yards) are likely to have led to the increase in woody canopy cover measured in chapter two. However, these disturbances may also lead to an increase in the mortality of trees and a change in the size class distribution of the harvested species (Luoga e*t al.*, 2004). This has been found in a recent study by Fisher *et al.* (2011) in BBR, where harvesting of a certain height class has changed the size class distribution of the affected savanna woodland. This change in the vegetation structure can result in a decline in the social and economic capital of the harvesters, if the quality of the fuelwood is diminished for a length of time such that is inconvenient to the harvesters (Scholes, 2009).

The drivers of woody canopy cover (Figure 4.1; right portion of the diagram) were explored in chapter three. They have been conceptually separated from the results from chapter two (Figure 4.1; left portion of the diagram) because they were obtained statistically using all the available data and spatially represent all the study sites. The results from chapter two, however, were obtained through spatially explicit analysis, and results inferred through the spatial patterns that were found, often visually. Thus, it makes sense to separate the results in this way. However, it does affect the woody canopy cover and can be interpreted through changes in the spatial configuration of the woody canopy cover, as is done above.

Interestingly, MAP was found to be the most important, and underlying geology the least important, driver of woody canopy cover across all sites, at all times measured, out of the five drivers analysed. Some authors have shown water to be the main determinant of woody cover in savannas (Walter, 1971; Walker e*t al.*, 1981; Walker & Noy-Meir, 1982; Coughenour & Ellis, 1993). This is important because it highlights the interplay between disturbances as drivers of woody canopy cover (such as the anthropogenic disturbance included in this study), and constant biophysical drivers. While spatially anthropogenic disturbances have created recognisable patterns in the woody canopy cover, the MAP may still be limiting or promoting the effects of those disturbances. So that areas that would, in an undisturbed state, have a high woody canopy cover would have been impacted less by a disturbance because the MAP leads to a more stable environment for woody vegetation. The idea of a ‘stable’ range of MAP was explored by Sankaran *et al.* (2005). They proposed that a MAP of up to 650mm leads to a ‘stable’ state in the amount of woody vegetation. Above 650mm MAP is considered an ‘unstable’ state where disturbances are more crucial in determining the amount of woody vegetation. This study reveals that this may be true, insofar as that anthropogenic drivers are causing identifiable disturbances, but the level of impact of the disturbance is determined, or at least influenced, by the MAP.

The distance from river and relative elevation were found to be the next most important drivers for woody canopy cover, of the five drivers analysed. These two drivers are obviously linked, in that rivers channels are found in the low parts of the landscape - the low values of relative elevation. These areas have high amounts of woody vegetation because of the availability of water, and may be harvested less because of difficulty in getting to the trees because of the topography (steepness of slopes near river channels) or thickness of vegetation, or not harvested because of aesthetic value. Also, the high availability of water would lead to a quick recovery of disturbed trees, and faster recruitment of trees.

While it has been acknowledged that anthropogenic drivers are impacting the vegetation landscape of BBR, the distance from villages was the second least important driver of woody canopy cover. This may be explained by the fact that the population densities of the villages are fairly high (Shackleton, 2000), and that the impact caused by the people is therefore not restricted to the areas immediately surrounding the villages. As trees adequate for harvesting become scarce around the villages, people will travel further to harvest fuelwood. Vehicles are also being used to harvest fuelwood, and people harvesting are not always form the closest village (Twine, 2005; Grainger, 2009). This may lead to harvesting not being correlated with the distance from the village. In 1944 the distance from the village was the second most important driver, and thereafter it was the least important driver after geology. This may be due to the people in the villages harvesting fuelwood closer to the villages because the supply was plentiful. Thereafter, as the supply of fuelwood in the areas immediately surrounding the villages dwindled, people harvested further away, and the correlation of woody canopy cover and village was lost. Fisher *et al.* (2011) found that as harvesting intensity increased, disturbance gradients around villages disappeared.

Geology was, surprisingly, the least important driver of woody canopy cover in this study. This may be because, at levels of high intensity use in the rangelands seen in this study coupled with the dwindling supply of fuelwood, harvesters became less selective of species harvested that differed on the two geological substrates. This would mean that there was no difference in harvesting rates on the two substrates, and therefore the underlying geology had no impact on the woody canopy density in this anthropogenically disturbed landscape.

While a trend may be seen in the increase of hot and cold spots at a landscape level, when analysing the persistence of these hot and cold spots within the context of high and low values for the drivers, separate patterns emerged. The riparian areas having a greater persistence of hot spots of wood vegetation is an interesting pattern that emerged, and may be important in terms of future, species specific, research. When spatially analysing the woody canopy cover, the emergence of a disturbance gradient around villages only in 2009 is an important finding, because it may point to a tipping point in terms of the magnitude of human disturbances that lead to such a gradient.

The large range of patterns in the hot spot analysis shows that the diversity of the landscape precludes a linear persistence model of the hot and cold spots of high and low woody canopy cover, respectively.

4.3 Limitations of the study

Due to the nature of the data, in that the aerial images captured only small areas of the ground and necessitated stitching many together in order to make up one site, of differing contrast levels, and two of the three sets were black and white (1944 and 1974), a large amount of data preparation was necessary before any analysis could be performed. Once the data were prepared, the analysis necessitated training the OBIA software (eCognition) in order to locate the tree canopies; this too was a laborious task. These object based images, in contrast to pixel based images, have a multitude of spectral, descriptive (such as shape and texture) and relational properties. The training of the software is absolutely necessary because the correct combination of these properties must be found in order to classify the objects for tree canopies. These time consuming operations meant that only three time periods were used (1944, 1974 and 2009) out of a possible five. With a smaller temporal resolution, changes that occurred in the woody canopy cover that may not be linear (such as an increase and then a decrease back to the original state) would have been missed. Similarly, the points in time when changes did occur are harder to ascertain because of this lack in temporal resolution.

For this study, five potential drivers of change were selected out of hundreds of potential drivers. The reasons for this are that the selected drivers’ data were available from the earliest data point (1944), and the drivers’ data were applicable across the entire study site. This limits the usefulness of the outcomes, although it was stressed that the level of importance is only a factor of the drivers analysed.

Throughout the study, care was given to differentiate between the measured woody canopy cover, and woody biomass. Woody canopy cover was used as a proxy to measure the woody vegetation, actual woody biomass was not measured or calculated. Because of this, the woody biomass may not be at the same level as the woody canopy cover, and inferences made may be incorrect. This situation is especially evident when it comes to the difference between a canopy and a coppicing harvested tree, or a large bushy plant and a tree. While the differences are hard to quantify via aerial images, especially those from 1944 and 1974 in this study, the patterns that emerged did give information as to what is driving the vegetation dynamics, and therefore what the structure of the vegetation is (when viewed from above via aerial imagery, in contrast to the structure of the vegetation when measured at plant height). Additionally, woody canopy cover is especially astute at picking up disturbances that may have been due to clearing and grazing of woody plants. In the same manner, it can be used to adequately detect large trees, however differentiating between smaller trees and coppicing trees remained a challenge.

4.4 Future research

Under the observed levels of village expansion, it is hypothesised that anthropogenic disturbances will continue to cause disturbances in the landscape until homogeneity in the vegetation distribution and size class distribution exists. This would start at a local level, and spread to a landscape level as resources decline. Disturbance gradients would start around villages, but would coalesce as the disturbance reached a high level.

Future research could entail using the findings of this study as a baseline, to which high resolution data from recent years is compared. This would give a good indication as to whether the findings using this data are actually a continuation of a trend that is occurring over a long period of time, part of a cyclical trend, or a deviation from the long term trends. With the exponential increase in humans in the area, and thus human disturbance, these recent data points can shed light on how these higher disturbances impact the landscape. The three temporal data points (1944, 1974 and 2009) were selected as they represented 65 years with roughly 30 years between each data point. However, more data are available, and indeed were available in this study, but were excluded because of the amount of time it takes to process each data point. If these were to be processed and analysed, the increased temporal resolution would help us understand whether the trends and patterns observed are directional, or if they change direction in the short term and change back. This would better inform monitoring and management decisions.

An important aspect of the dynamics of the landscape is the three dimensional structure of the vegetation. This has been explored in other research (Fisher, 2011; Fisher, 2013), and has led to insights that cannot be ascertained without that data. The single most problematic feature of aerial data when trying to ascertain woody biomass, is that inferring a tree from a canopy does not include the height of the tree, and indeed this study suffered from not being able to distinguish trees from coppicing plants. By including such height data, the structure of the woody vegetation can also be measured, and impacts on this structure through disturbances can be analysed. This is important because it can give insight into the way human disturbances are impacting the vegetation, and not just whether a disturbance is present or not. Future research may incorporate three dimensional height data, such as LiDAR, into the recent high resolution data over the area, in order to expand the findings here and enhance our understanding of the dynamics of this heavily utilized landscape.

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