PARTICIPATORY SAVANNAH MANAGEMENT: A COMMUNITY BASED INTEGRATED BIOCHAR SYSTEM FOR SOUTH AFRICA

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ABSTRACT

The Limpopo Province is the poorest region in South Africa. Strategies to alleviate poverty have done little to empower the majority of small, rural, emerging black farmers. Unsustainable farming practices have led to widespread soil degradation, bush encroachment, loss of biodiversity and declining productivity. Integrated biochar systems can be used to help reverse environmental degradation, increase yield and improve resource use efficiency. Species encroachment in native savannahs, in particular, has reduced browse quality for wildlife. Selective bush harvesting by local community members removes problem species and provides income from firewood sales. On the household scale, combustion of fuel wood in biochar cook stoves, with culturally sensitive designs, can improve fuel use efficiency and produce biochar for soil amelioration. The integrated biochar system enables shared stewardship of fragile environments and encourages use of agroecological principles to minimize adverse impacts to savannahs and help restore their biodiversity.

BIOGRAPHICAL SKETCH

Christian Adlai Pulver was born and raised in Colombia. He received his BA in International Studies, with a focus on International Security and Arms Control, from the University of Illinois, Champaign/Urbana. He served for 2 years as a Peace Corps Volunteer in Bolivia as an agriculture extension agent specializing in vegetable and flower production at high altitudes using never-tried before adobe greenhouses. Christian joined the Department of Crop and Soil Sciences in 2010. His research focuses on the use of integrated biochar systems in semi-arid northern South Africa.

I dedicate this thesis to my parents, Edward and Carmenza, for their unrelenting support in my quest to innovate new technologies for small holder farmers around the world.

I also dedicate this work to the village communities in Bolivia where I worked for two years that led me to study at Cornell University to develop simple agronomic solutions for farmers in semi-arid regions.

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I also thank Dr. Chris Wien for believing in me since the first day I arrived at Cornell University. His support of my work has kept me thinking and pushed me to unravel the mystery behind biochar. As my first adviser, I am grateful to have his support for international agricultural work.

Last, I gratefully acknowledge everyone who has been a part of our South African project, including friends at ZZ2. To the many people that I have met along the way during my Master's research, I am thankful for all the advice and encouragement that has sustained my momentum for the past years.

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LIST OF ABBREVIATIONS

LIST OF SYMBOLS

PREFACE

CHAPTER 1: INTRODUCTION

1.1 Impact of bush encroachment in the Cordier Conservancy

Savannahs are the most extensive ecosystem in the world and sustain millions of people through its seemingly limitless natural capital. Africa's sub-Saharan savannahs are the world's largest, encompassing 10.33 x 10^6 km^2 with an estimated 313 million inhabitants deriving their sustenance from it (White et al., 2000). However, these resources are finite and increasingly threatened by human activity. Overconsumption of natural resources has led to extensive degradation of crop land, exacerbated desertification, and has had disparate effects on human welfare as food scarcity pervades. Ecosystem services are inherently linked with human welfare, and their functions cannot be separated from the people dependent on them. Large-scale land conversions of sub-Saharan savannahs have been accelerated by human activity, mainly through agricultural extensification, with pronounced losses of biodiversity (Gibson, 2009). Resource use intensity coupled with increasing food demand has transformed once vibrant savannahs into vulnerable and critically threatened biomes. One such area is South Africa's Low Bushveld that has succumbed to the invasion of encroaching tree species resulting from over-grazing and exhaustive farming practices. Global climate change has compounded this problem. Mitigating habitat and ecological losses requires nuanced approaches that reverse degradation and restore ecosystem services, while simultaneously improving the welfare of humans and wildlife.

Bush encroachment is a serious problem presently threatening South Africa's native savannahs with dire consequences. In Limpopo's Low Bushveld, encroaching tree species have successfully outcompeted indigenous vegetation for sunlight, soil moisture and nutrients, and ground-cover (Richardson and van Wilgen, 2004; van Wilgen et al., 2008). Bush encroachment, as defined by Brown and Archer (1999), does not necessarily signify exotic species, but instead is attributable to increased abundance of undesirable indigenous trees or shrubs resulting from disturbances or deterioration of savannah ecosystem functions. Reductions in net primary productivity and herbaceous cover are major consequences of bush encroachment that are driven by increases in tree density and associated woody biomass (Smit, 2004). Increases in non-herbaceous cover have shifted grassland biomes into scrub forests, altering ecosystem functions and decreasing productivity (Scholes, 2003).

Water is a limiting resource in semi-arid savannahs. Bush encroachment significantly decreases soil water storage by increasing water use and depleting groundwater via extensive root systems (Smit and Rethman, 2000). This in turn depresses productivity of herbaceous species and decreases grazing capacity, while increasing the risk of erosion. The impact of invasive tree species on South African savannahs has been well documented, but management options for controlling and restoring ecosystem functions in encroached savannahs have demonstrated varied responses (Teague and Smit, 1992; Smit, 2002). Smit (1998, 2004) recommends that successful restoration of bush-encroached areas must be both economically and ecologically viable to increase beneficial woody plants and herbaceous cover and to prevent re-encroachment or exacerbate problems further.

In this context, this study was conducted between January 2010 and August 2011 in a highly encroached, managed savannah called the Cordier Conservancy. As a game reserve, wildlife health is correlated to the quality and availability of browse that sustains herds on the conservancy. The ramifications of a system in disequilibrium are over-grazing (higher animal density in less degraded areas), less herbaceous cover from trampling, thickets preventing migration of wildlife, erosion, and a lower carrying capacity. The Cordier Conservancy was once pastureland for cattle and, throughout the years, has endured frequent cycles of abandonment and clear-cutting that have led to its current condition. In this thesis, I investigate management options to reduce bush encroachment, enhance savannah ecosystem functions, increase wildlife carrying capacity, and facilitate the engagement of peripheral communities in the Vhembe district in the stewardship of privately owned land.

The Vhembe district of South Africa is among the poorest regions in South Africa (Department of Agriculture, 2007). A once semi-independent state for Bantustan people under apartheid, the Vhembe district is enduring increasing unemployment, food insecurity, and a "brain drain" as more educated people leave the area to pursue more lucrative ventures in other areas of South Africa (Obadire et al., 2010). Of the 1.25 million inhabitants of the Venda region, 65.2% or approximately 813,467 people are living in poverty and almost 50% are unemployed. Subsistence farming is the dominant economic activity for the majority of the population as 80% do not reach secondary school or matriculate. Largely unskilled and dependent on low-productivity farming, ameliorating food insecurity and malnutrition are salient needs for the Venda people. Integrating small farmers from this region with resources outside of their homeland could provide a means for improving food production and human welfare. Limited knowledge of the depths of poverty in the region coupled with national programs incentivizing large agricultural enterprises for export markets has left this region largely excluded. Luow et al. (2007) argues that integration of subsistence farmers into the South African food supply chain requires efforts to (i) revamp extension services to train farmers to improve product quality and marketing; (ii) reconcile geographical displacement with logistical support to feed domestic demand for fresh produce; (iii) decentralize markets and create facilities to reduce costs to farmers; and (iv) provide a means for farmers to access vital and affordable inputs. As a semi-arid region, climate fluctuations and degraded soils further constrain Venda farmers from potential inclusion into national agricultural markets.

The introduction of an integrated biochar system could help aggrade soil quality for subsistence farming and provide resilience against both abiotic and biotic stresses through the special characteristics of biochar (see Chapter 1). An integrated biochar system involving small-holder farmers and new technologies such as pyrolytic cook stoves can be a practical approach benefiting both the environment and the people dependent on it. In this chapter, I investigate the potential of linking subsistence farmers with selective culling of bush encroached private conservancies to produce biochars for amending soils using culturally sensitive, locally-produced pyrolytic cook stoves. These stoves can replace indigenous three stone fires and thus improve indoor air quality, enhance biomass use efficiency and could become an additional product for local pottery makers to produce.

1.2 Background and location

This project, called AfroChar™, is a partnership between ZZ2 (Bertie van Zyl Pty. Ltd) and the Mashamba Pottery Factory Co-operative. The Mashamba Pottery Factory Co-operative is located in Mukondeni, 23°15'4.38"S and 30° 6'46.80"E. The cooperative is run by an organization of women who fabricate and sell artisanal pottery. In 2010, the AfroChar™ project approached the Mashamba Pottery Factory Co-operative to see if they could replicate a clay Anila cook stove produced in Kenya for the production of biochar. Forty-seven women from the Mashamba Pottery Factory Cooperative participated in the stove competition. A demonstration stove was given to the factory in 2010. By 2011, over 30 stove designs were available for testing. Women involved in the project received compensation in the form of woody biomass and tomatoes donated by ZZ2. Capacity building initiatives to improve clay baking were also introduced in 2010. This involved using rulers to properly measure stove dimensions, consulting on improving clay quality to prevent cracking during firing, and grant proposals to raise money to repair a broken electric kiln.

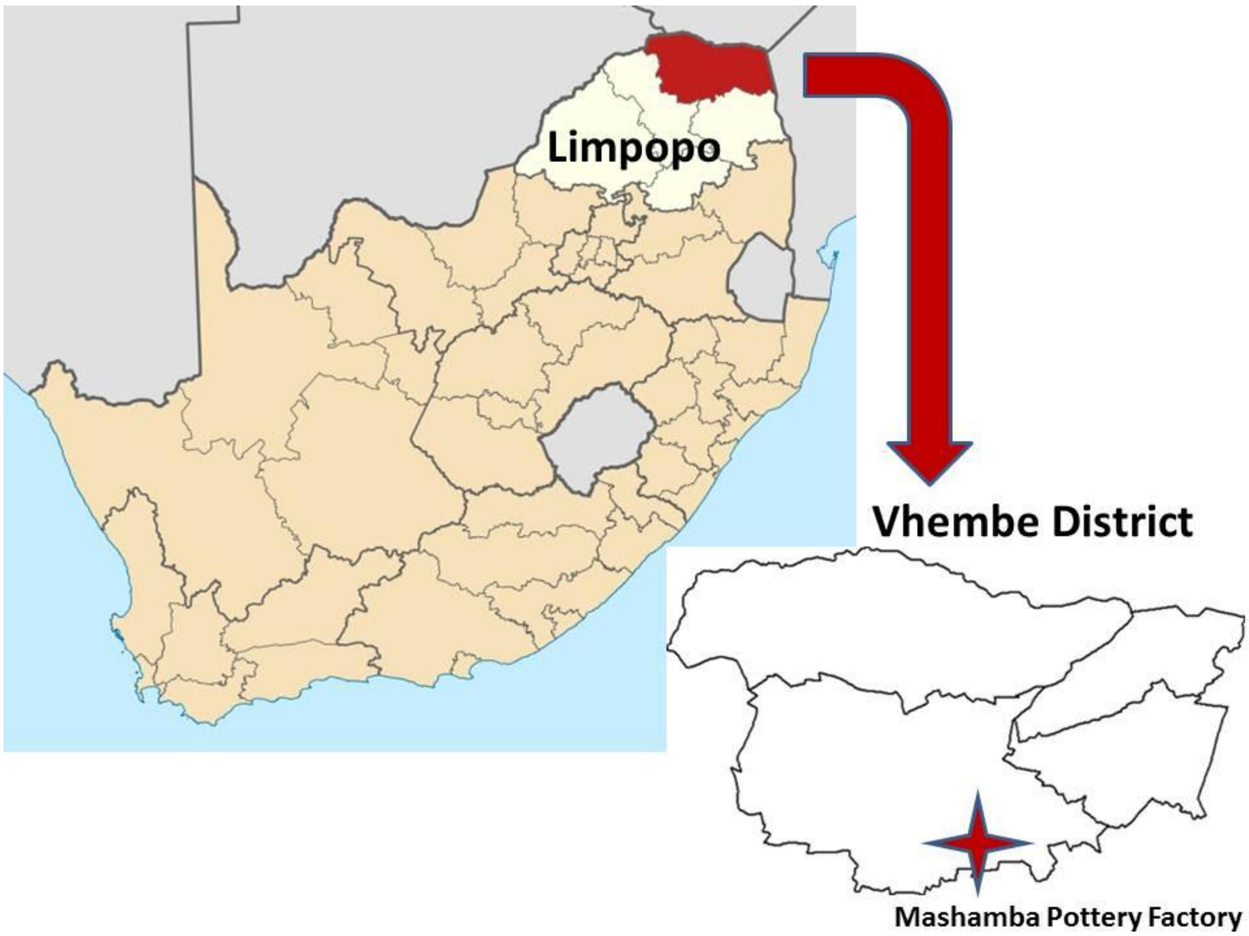

Figure 1.1   Location of Mashamba Pottery Factory

Harvesters from Mashamba and other nearby villages participated in a pilot project in the Cordier Conservancy to selectively harvest encroaching tree species. Over 800 harvesters participated in the 2009 – 2010 thinning operation in the Cordier Conservancy. These harvesters were recruited by word of mouth and were self-organized during harvesting periods. Local foremen and ZZ2 Game Managers ensured that only harvestable species were being culled and that no large trees were being removed. Daily limits on harvesting were 100 metric tonnes of biomass.

As wood is the main source of cooking fuel, the depletion of woody biomass around the Mashamba area necessitates alternative sources of fuel-wood usually found in distant areas or in private land inaccessible to local inhabitants. The search for fuel-wood is often the responsibility of the women in the household who have to venture many kilometres in order to obtain wood to cook food for their families. Makhado et al. (2009) studied fuel-wood usage in six villages near Venda and estimated that the average household consumed 6.8 kg of fuel-wood daily for cooking. Maximum consumption was 8.2 kg per household. In these villages, three-stone fires were the main means used for cooking. The adoption of a pyrolytic cook stove could reduce energy consumptions by over 10 J yr^{-1}. Torres et al. (2011) found that three-stone fires consume 46.82 GJ of energy per annum; while an Anila style pyrolytic stove consumes 37.44 GJ yr^{-1}. These authors found that wood energy use was reduced by 29% and this could be attributed to use of the pyrolytic stove. Net dry biochar yields from the Anila pyrolytic stove were <1.0 to 1.5 t per annum, depending on household size and fuel-wood availability (Torres et al., 2011).

Dependence on fuel-wood for rural South Africans remains high in isolated areas like Venda, where electricity is lacking or too expensive for the average household (Shackleton, 1993). Fuel-wood is a prized commodity, and the lack of electricity further intensifies this demand. Linking fuel-wood demand with pyrolytic stoves to cook food and produce biochar can be a way of ameliorating household level land degradation if private land owners seeking to rehabilitate encroached savannahs participate in the co-stewardship of these natural resources. This novel concept touches delicate issues of past-apartheid segregation, but can be a new means for white-owned enterprises to engage with resource poor farmers. The threat of encroaching species can be an opportunity beyond biochar production and could help facilitate the inclusion of subsistence farmers in national markets.

Alternative sources of energy are non-existent and have placed pressure on surrounding environments as resources near homelands become depleted. Without communal sources of fuel-wood, the exploitation of the lowveld savannah will continue and create irreversible damage to an already vulnerable biome. Private lands, like the Cordier Conservancy, offer fuel-wood biomass that can be mutually stewarded similarly to communal woodlots as described by Shackleton (1993). Bush encroachment abatement can be a participatory activity where carbon could be managed to restore savannah ecology by the pyrolysis of coppiced bush encroaching species, and ultimately produce biochar as a soil amendment.

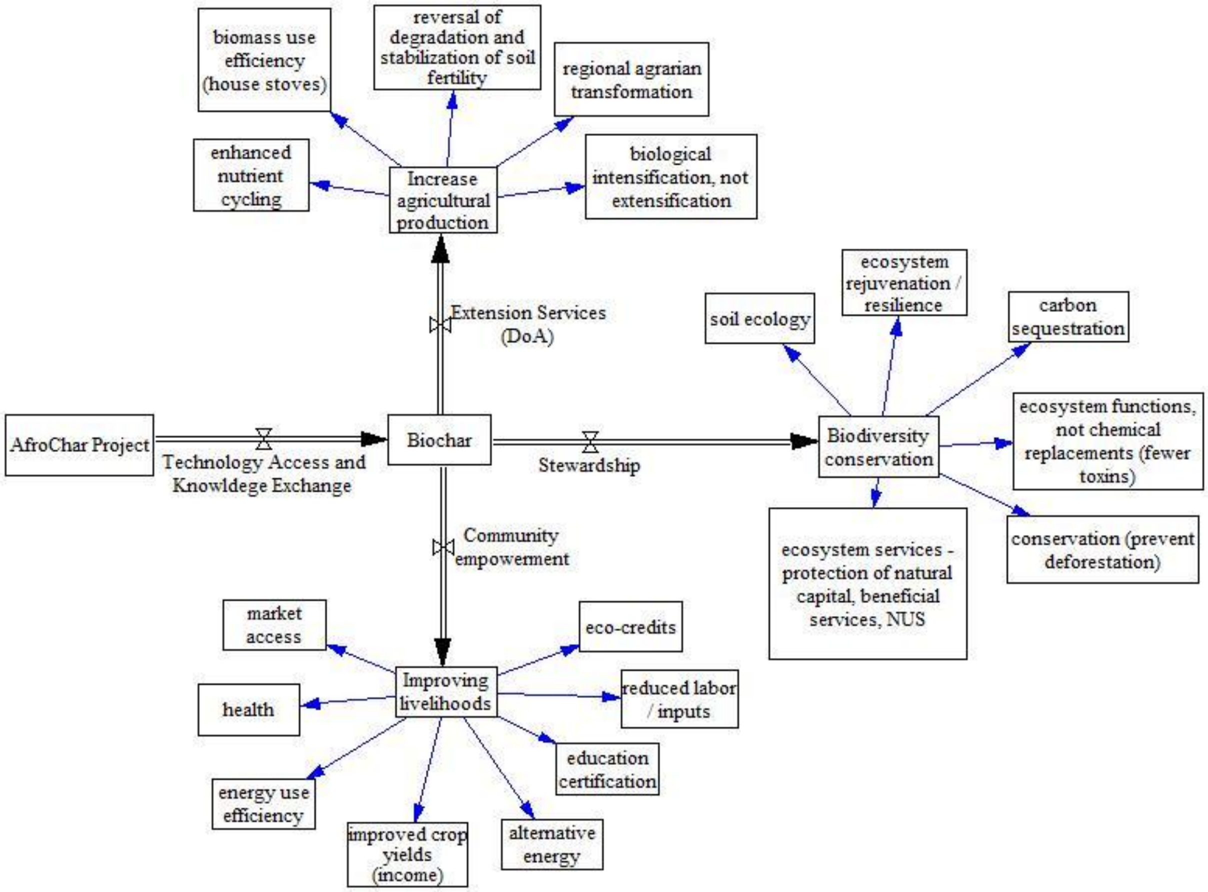

Figure 1.2 Conceptual framework for locally produced biochars.

1.3 Research problems, aims and hypotheses

Presently, the Cordier Conservancy is a functioning wildlife game-reserve undergoing serious transformations to address the following problems:

(i) Fire regimes that have shown inconclusive progress in removing encroaching woody species. The higher the density of trees, the less fuel (annual biomass litter fall combined with herbaceous cover) available to effectively kill encroaching trees. Additionally, certain fire regimes have killed beneficial trees and favored re-encroachment of undesirable woody species.

(ii) High tree densities that restrict the migration of wildlife, and inhibit hunters and eco-tourists from game-spotting (visibility of game).

(iii) Browse quality of encroaching trees that are less palatable and unreachable by ungulates.

(iv) Mechanical clearing that is too expensive and impractical due to topography.

(v) Herbicidal controls that are effective, but expensive and can kill beneficial species. The rising costs of herbicides combined with labor required to spray have led to abandoning herbicidal controls.

Mitigating bush encroachment requires multiple approaches and an understanding of the ecosystem. Given the mandate to increase herbaceous cover, grazing capacity, biodiversity and profitability, the following objectives were set to help restore the Cordier Conservancy:

(i) To identify and assess the abundance of both woody and herbaceous species (botanical composition) and their forage quality.

(ii) To determine the best method(s) of thinning encroached areas and follow-up prevention strategies.

a. Fire

b. Chemical thinning

c. Mechanical thinning

d. Hand-thinning

(iii) To monitor the influence of hand-thinning on botanical composition, coppice regrowth rates, herbaceous cover, soil and veld condition; and create restoration parameters to indicate progress in increasing carrying capacity and improving ecosystem health.

(iv) To produce culturally appropriate pyrolytic cook stoves in cooperation with harvesters and local communities. Calculate fuel-wood consumption using currently used three-stone fires and the availability of encroached biomass. Calculate the offset of gross carbon (C) emissions from increasing net primary productivity (NPP) and sequestering bush-char in the soil in comparison to current practices.

(v) To analyze biomass feedstocks and resulting biochars to produce a bush-derived char appropriate for intended soils.

(vi) To scientifically improve biochar characterization methodologies. At the industrial level, to form a group of engineers dedicated to improving stove performance. At the household level, to develop a classification system for bush chars feasible for use by small-holder land managers.

(vii) To formulate a system that integrates rural demand for fuel-wood with encroached privately owned land to aid in restoring savannah health and producing biochars that can help reverse soil degradation at the household level.

CHAPTER 2 BIOCHAR LITERATURE REVIEW

2.2 Biochar Literature Review

Biochar is produced by 'thermally decomposing' organic materials under low temperature and low oxygen conditions in a process called pyrolysis (Lehmann, 2007a). The resulting biochar has a dramatically different composition and physical and chemical properties than the original biomass. Plant biomass, also referred to as feedstock, is typically composed of cellulose, hemicellulose and lignin as the dominant structural C compounds, with varying nutrient contents and densities. During pyrolysis, C bonds are rearranged into highly enriched condensed C compounds with aromatic rings (Czimczik et al., 2002). Aromatic C compounds are difficult to decompose and are retained in soil for long periods of time, thus increasing C sequestration in soil. Therefore, biochar quality depends strongly on the feedstock used. Changes in the chemical and physical structure of C compounds in the feedstock material directly influence the longevity of biochar prepared from that material when applied to soil.

Interest in biochar began with the study of the terra preta soils (dark earths) in the Brazilian Amazon that contain large amounts of pyrolyzed C and exhibit impressive soil properties that are maintained over millennial time-scales (Glaser et al., 2002; Glaser and Woods, 2004; Glaser et al., 2009). The resistance to decomposition of this pyrolyzed C results in its long-term retention in soil and associated retention of important plant nutrients (Baldock and Smernik, 2002). The terra preta soils appear as islands of high soil fertility in a landscape dominated by persistent soil infertility. The high fertility of the terra preta soils is strongly related to the presence of black carbon and their high cation exchange capacity (CEC). Research conducted to elucidate the effect of biochar in soils is in its infancy, with substantial evidence demonstrating positive effects in low fertility soils. Re-creating the characteristics of terra preta soils by adding charred biomass to infertile soil is a promising approach to restore fertility in the degraded soils in South Africa. An integrated biochar system could help to restore ecological functions in a degraded savannah, while concomitantly supplying recalcitrant C to the agricultural soils of local small-holder farmers.

Current studies on biochar have shown that it has a high adsorptive capacity and high chemical activity (Liang et al., 2006; Downie et al., 2007). Biochar has been shown to increase nutrient and water retention when added to soil (Tryon, 1948; Glaser et al., 2002;), and has been shown to increase plant productivity as a result of rhizosphere-microbe community interactions in field experiments (Lehmann, 2006; Major, 2009; Warnock et al., 2007). The primary benefits of adding biochar to the soil are (i) increasing the CEC (Liang et al., 2006), (ii) increasing soil nutrient retention (Hammes and Schmidt, 2009; Steiner, 2008), (iii) increasing water holding capacity, (iv) adding nutrients (high ash chars), and (v) altering soil pH (Glaser et al., 2002; Chan and Xu, 2009).

Physically, biochar is a very porous material. This porosity results in a high surface area, which can range from 10 to over 1000 $m^2 g^{-1}$ (Laine et al., 1991), depending on the nature of the feedstock, pyrolysis temperature, oxygen availability and processing time. The porosity of biochar and its resulting surface area depend on the composition (lignin, cellulose and hemicellulose contents) of the biomass feedstock and its density, relative to pyrolysis conditions (Gundale and DeLuca, 2006). Pyrolysis conditions interact with feedstock characteristics to produce chars with highly varying characteristics. For example, using the same feedstock but varying the pyrolysis conditions can result in an acid, neutral or alkaline char. Biochar porosity is also affected strongly by pyrolysis conditions as noted above. High temperatures and longer pyrolysis times reduce porosity; shorter pyrolysis times and lower temperatures increase porosity (Keech et al., 2005). Thus, all biochars are not created equal. The aim of producing biochar as a soil amendment is to address the constraints of the soil into which it is placed.

Biochar porosity is particularly important because it affects the ability of microbes to colonize its surfaces and increases total reactive surface area. The porous structure of biochar provides microbial populations a refuge and environmental conditions that affect their activity and dictate which processes are likely to dominate in amended soils. Biochar pores provide surfaces for fungal hyphae and bacteria to colonize. They also provide a refuge for bacteria that protects them from grazing. For example, the average pore diameter of biochar particles is less than 16 µm, while soil bacteria range in size from 1-4 µm and soil fungi from 2-64 µm in diameter (Thies and Rillig, 2009). Soil grazers range in size from 8–100 µm for protozoa and well over 100 µm for soil micro-arthropods. Thus, biochar can promote the physical protection of soil bacteria and may protect fungal hyphae from grazing, thus improving the persistence of these beneficial organisms in the soil.

Microbial community dynamics in biochar-amended soils display extraordinary and consistent evidence that biochars improve critical ecological processes (Ogawa et al., 1983; O'Neill et al., 2009; Kim et al., 2009). The effects of biochar on mycorrhizae have been studied in relation to its function as a refuge and as an inoculum carrier. Warnock et al. (2007) proposed four key mechanisms by which biochar may influence mycorrhizal ecology, namely by altering (i) nutrient dynamics and/or soil physico-chemical parameters, (ii) the effects of either beneficial or detrimental microorganisms, (iii) plant/mycorrhizal signalling processes or detoxifying allelochemicals, and/or (iv) serving as a refuge from fungal grazers.

Evidence supports the beneficial use of biochar in tropical agricultural systems, however, little is known about the potential use of an integrated biochar system in an African savannah. In the following chapters, I investigate the potential benefits of amending semi-arid savannah soil with bush-derived biochars.

2.2 Pyrolysis

Pyrolysis is the thermal decomposition of biomass under anoxic or anaerobic conditions to produce solid chars, liquids and gases (Bridgewater and Peacocke, 2002; Demirbas and Arin, 2002; Antal and Gronli, 2003). Unlike direct combustion and gasification, pyrolysis limits oxidizing reactions at lower temperatures (< 750°C) (Bridgewater and Diebold, 1999; Ringer et al., 2006). During pyrolysis, biomass is "burned off" or lost with the volatilization of organic compounds, dehydration, and subsequent shrinking from the rearrangement of geometric structures through sintering, fusion, melting or plastic deformation (Cetin et al., 2004; Boateng, 2007; Downie et al., 2009). The extent of reduction and resulting structure depend on the original biomass quality and production conditions (Antal and Gronil, 2003; Novak et al., 2009; Downie et al., 2009).

2.3 Char morphology

Production conditions influence char morphology through heating rate, hold time of the highest heating rate, oxidizing reaction time and kinetic reactions, atmospheric pressure, and feedstock pre-treatment preparation (Lua et al., 2004; Downie et al., 2009). Biomass feedstock directly influences the physical geometry of biochar as different organic compounds thermally decompose at varying heating rates. Sjostrom (1993) found that the organic components and their proportions in biomass feedstock greatly influence biochar physical structures at lower temperatures. Hemicellulose, cellulose and lignin thermally degrade with increasing temperatures as feedstock molecules become solid chars and liquids with the vapour loss of non-condensable gases. Hemicelluloses degrade at lower temperatures of 200ºC to about 260ºC and produce mainly non-condensable vapours while celluloses degrade at 240ºC to 350ºC and produce condensable vapours and low molecular weight compounds (Sjostrom, 1993; Yang et al., 2007). At 280º to 500ºC, lignin degrades slowly due to its location in the cell wall and recalcitrant aromatic composition (Sjostrom, 1993; Saxena and Brown, 2005). Lignin produces both condensable and non-condensable vapours but mainly char (Mohan et al., 2006). Proportions of these organic compounds vary by plant species, and therefore different feedstocks yield different chars, liquids and gases.

Production conditions influence char morphology and yield. Heating rate and highest treatment temperature, atmospheric pressure, kinetic reaction time, vapour residence time, feedstock preparation and pre-treatment, and pyrolytic chamber design affect the resultant biochar structure (Downie et al., 2009). It has been shown repeatedly that, of these parameters, the highest heating rate has the greatest impact on biochar geometry (Antal and Gronli, 2003; Lua et al., 2004; Boateng, 2007; Downie et al., 2009). However at lower temperatures (<450ºC), biomass quality is the most important factor controlling the physical properties of biochar (Cetin et al., 2004; Lua et al., 2004; Boateng, 2007). Table 2.1 illustrates different production processes with respective heating temperatures, heating rates and product yields.

Table 2.1 Analysis of pyrolytic production processes

Process	**Temperature** (°C)	**Heating rate**	**End-products**
Torrefaction	230-300	Very low	Charcoal
Slow pyrolysis	380-530	Low	Char, bioliquids, gas
Fast pyrolysis	380-530	High	Bioliquids (some char)
Combustion	700-1400	Very high	gas
Gasification	> 750	Very high	gas

2.4 Agronomic analysis

Field trials and laboratory experiments have demonstrated the agronomic potential of amending soils with biochar. The direct and indirect mechanisms attributable to positive crop responses are relatively unknown, but multiple studies shown concomitant crop responses with the addition of biochar to the soil (Ogawa, 1994; Lehmann et al., 2003; Chan et al., 2007; van Zwieten et al., 2007; Rondon et al., 2007; Warnock et al., 2007; Steiner et al., 2008; Shackley and Sohi, 2010; Verheijen et al., 2010; Woolf et al., 2010 Atkinson et al., 2010). Jeffrey et al. (2011) conducted a review of biochar amended soils and the effect of biochar on crop productivity.

Table 2.2 Meta-analysis of biochar amended soils. Source: adapted from Jeffrey et al. (2011)

Parameter	Sub-grouping	Number of studies	References
Soil texture	Coarse	7	Gaskin et al. (2010), Ishii and Kadoya (1994), Lehmann et al. (2003), Major et al. (2010), Nehls (2002), van Zwieten et al. (2009), Wisnubroto et al. (2010)
	Medium	8	Asai et al. (2009), Blackwell et al. (2007), Chan et al. (2007), Chan et al. (2008), Hossain et al. (2010), Kimetu et al. (2008), van Zwieten et al. (2009), Yamato et al. (2006)
	Fine	1	Asai et al. (2009)
pH class (<5, 5-6, >6)	<5	7	Blackwell et al. (2007), Chan et al. (2007), Chan et al. (2008), Hossain et al. (2010), Major et al. (2010), van Zwieten et al. (2009), Yamato et al. (2006)
	5-6	8	Asai et al. (2009), Blackwell et al. (2007), Chan et al. (2008), Chidumayo (1994), Gaskin et al. (2010), Kimetu et al. (2008), Lehmann et al. (2003), Wisnubroto et al. (2010)
	>6	5	Asai et al. (2009), Gaskin et al. (2010), Ishii and Kadoya (1994), Kimetu et al. (2008), van Zwieten et al. (2009)
Latitude	Tropical	7	Asai et al. (2009), Chidumayo (1994), Kimetu et al. (2008), Lehmann et al. (2003), Major et al. (2010), Steiner et al. (2007),

			Yamato et al. (2006)
	Subtropical	7	Blackwell et al. (2007), Chan et al. (2007), Gaskin et al. (2010), Hossain et al. (2010), Ishii and Kadoya (1994), Nehls (2002), van Zwieten et al. (2009)
Region	Africa	2	Chidumayo (1994), Kimetu et al. (2008)
Feedstock	Poultry litter	1	Chan et al. (2008)
	Acacia bark	1	Yamato et al. (2006)
	Paper pulp and wood chips	1	van Zwieten et al. (2009)
	Wastewater sludge	1	Hossain et al. (2010)
	Green waste	2	Asai et al. (2009), Major et al. (2010)
	Wood	8	Chan et al. (2007), Wisnubroto et al. (2010), Lehmann et al. (2003), Steiner et al. (2007), Chidumayo (1994), Nehls (2002), Kimetu et al. (2008), Blackwell et al. (2007)
	Peanut hull	1	Gaskin et al. (2010)
	Pine chips	1	Gaskin et al. (2010)
	Biosolids	1	Wisnubroto et al. (2010)
Biochar application rate	1-39 t ha^{-1}	11	Asai et al. (2009), Blackwell et al. (2007), Chan et al. (2007), Chan et al. (2008), Gaskin et al. (2010), Hossain et al. (2010), Kimetu et al. (2008), Major et al. (2010), van Zwieten et al. (2009), Wisnubroto et al. (2010), Yamato et al. (2006)
	40-79 t ha^{-1}	5	Chan et al. (2007), Chan et al.

			(2008), Ishii and Kadoya (1994), Lehmann et al. (2003), Yamato et al. (2006)
	>80 t ha^{-1}	2	Chan et al. (2007). Lehmann et al. (2003)
Fertilizer co-addition	None	10	Asai et al. (2009), Chan et al. (2007), Chan et al. (2008), Chidumayo (1994), Gaskin et al. (2010), Ishii and Kadoya (1994), Nehls (2002), van Zwieten et al. (2009), Wisnubroto et al. (2010)
	Inorganic	10	Asai et al. (2009), Blackwell et al. (2007), Chan et al. (2007), Chan et al. (2008), Gaskin et al. (2010), Kimetu et al. (2008), Steiner et al. (2007), van Zwieten et al. (2009), Wisnubroto et al. (2010)
	Organic	4	Asai et al. (2009), Hossain et al. (2010), Lehmann et al. (2003), Nehls (2002)
	Both	2	Asai et al. (2009), Major et al. (2010)
Crop type	Rice	2	Asai et al. (2009), Nehls (2002)
	Wheat	2	Blackwell et al. (2007), van Zwieten et al. (2009)
	Radish	3	Chan et al. (2007), Chan et al. (2008), van Zwieten et al. (2009)
	Maize	4	Gaskin et al. (2010), Kimetu et al. (2008), Major et al. (2010), Yamato et al. (2006)
	Tomato	1	Hossain et al. (2010)
	Cowpea	2	Lehmann et al. (2003), Yamato et

			al. (2006)
	Ryegrass	1	Wisnubroto et al. (2010)
	Soybean	1	van Zwieten et al. (2009)
	Sorghum	1	Steiner et al. (2007)
Experiment design	Pot	7	Chan et al. (2007), Chan et al. (2008), Hossain et al. (2010), Ishii and Kadoya (1994), Lehmann et al. (2003), van Zwieten et al. (2009), Wisnubroto et al. (2010)
	Field	7	Asai et al. (2009), Blackwell et al. (2007), Chidumayo (1994), Gaskin et al. (2010), Kimetu et al. (2008), Major et al. (2010), Yamato et al. (2006), Steiner et al. (2007), Nehls (2002)

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CHAPTER 3 STUDY AREA

3.1 Geographical location

The Low Sour Bushveld region in the Limpopo Province of South Africa is located north of the Highveld Grassland, west of the Mopane Low Veld region, south of the Limpopo River, and west of Kruger Park (Figure 2.1). Cowling et al. (1997) characterized this region as the Low Sour Bushveld, with an arid climate consisting of a cool, dry season and a hot, wet season. Vegetation in this ecosystem is composed of intermixed broad-leaved and fine-leaved tree species, depending on growing conditions and intensity of disturbances (Cowling et al., 1997). The Highveld plateau protects this low lying plain from frost and cold winters, providing warmer temperatures, averaging 21°C, year round (van der Muelen, 1980). As a result, Cowling et al. (1997) categorized this region as primarily broad-leaved savannah located in an arid environment with an average of 250 – 650 mm precipitation per annum.

With the advent of geographical information systems (GIS), biome mapping has improved the ability to identify, geographically, the location of distinct savannahs. Using the Soil and Terrain (SOTER) database for South Africa (Dijkshoorn et al., 2008), a closer examination of the region places the Cordier Conservancy within the Tzaneen Sour Bushveld. The Tzaneen Sour Bushveld covers a total area of 343,000 ha, with approximately 3% of the biome protected and 41% transformed into large agricultural operations. The Biodiversity Act 10 of 2004 commissioned the South African National Biodiversity Institute (SANBI) to classify ecological biomes according to their condition and vulnerability to both biotic and abiotic risks. Results from the SANBI (Mucina and Rutherford, 2006; Musil et al., 2007) surveys concluded that the Tzaneen Sour Bushveld is in imminent threat of irreversible loss of natural habitat and therefore it is listed as a vulnerable biome.

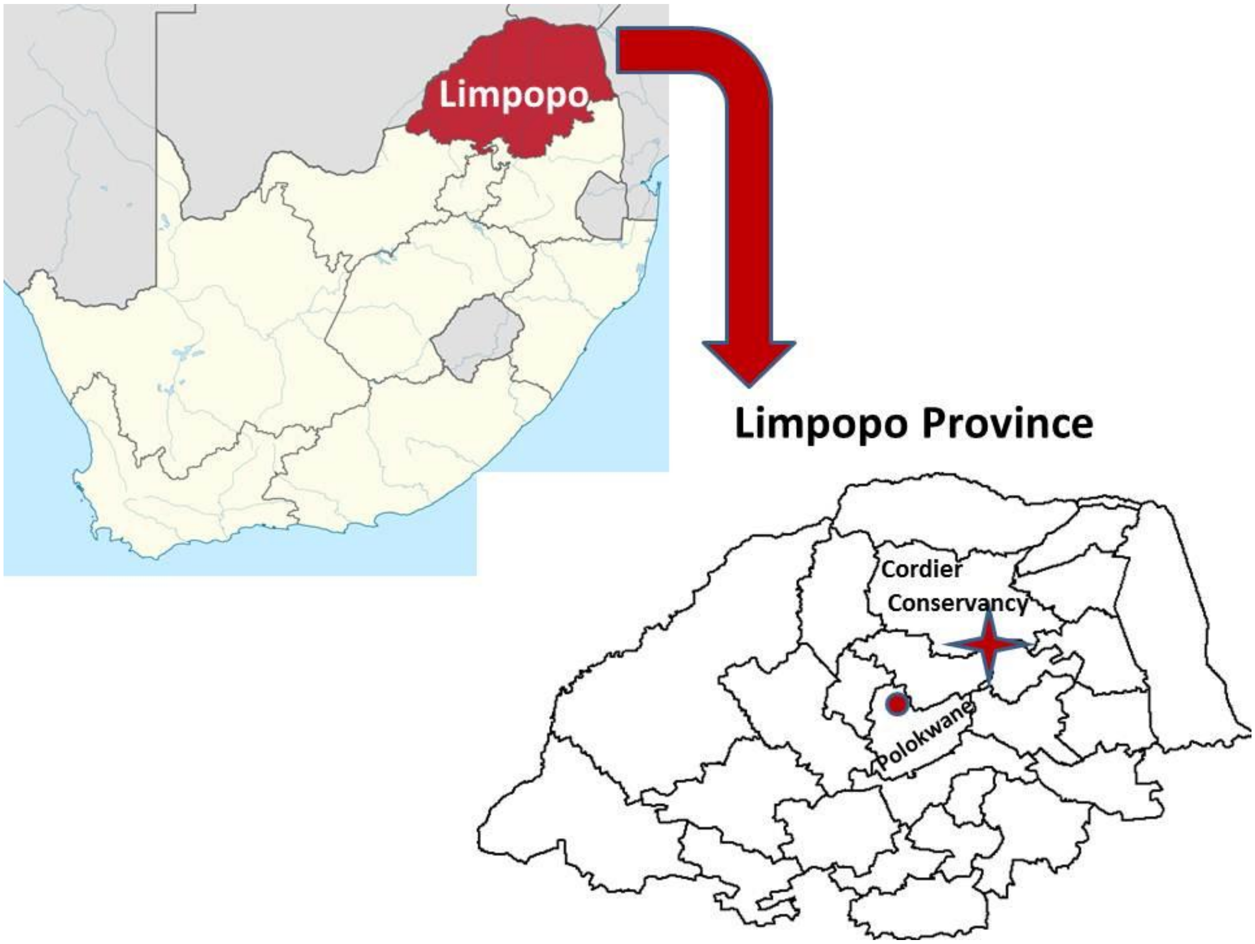


Figure 2.1 Location of Cordier Conservancy

The Cordier Conservancy is located 23°30'12.72"S and 30° 9'25.27"E; approximately 84 km northeast of Polokwane. Spanning 4,600 ha, the Cordier Conservancy is a private wild game reserve stocked with 2,500 animals valued at 2.6 million Rand.

6.1.0.5001. (10/17/2011). *Limpopo, South Africa, 23°31'20.20"S, 30° 7'38.17"E, 723 m.*

Figure 2.2 Cordier Conservancy parcel (1:92347)

3.2 Climate

Weather data for the Cordier Conservancy was collected using weather stations starting in 2004 through 2011 (ZZ2 Weather Database). Erratic rainfall patterns between those periods show a wide variation of precipitation ranging from 337 - 824 mm of rainfall per annum. The wet season is typically from early November to late March, with an extended dry season interlude. The microclimate of the Cordier Conservancy is influenced strongly by topography; having a mountainous ridge sharply sloping into the broader Mookesti Valley.

3.2.1 Temperature

Temperature readings describe a moderately humid climate with a long frost-free winter. As shown in Figure 3, approximately 200 days of the year receive less than 10 mm of rain. Temperature fluctuations for 2004, 2008, 2009 and 2010 are presented in Table 1. Average low and high temperatures remained consistent throughout the study, despite varying rainfall. Low et al. (1996) described similar conditions in other sour-mixed bushvelds, with an average temperature of 21°C, with a low of -8°C and a high 40°C.

Table 3.1 Cordier Conservancy climate data for 2004, 2008, 2009, 2010 and 2011.

YEAR	MEAN LOW TEMP. (°C)	LOWEST TEMP. (°C)	MEAN HIGH TEMP. (°C)	HIGHEST TEMP. (°C)	MEAN HEAT INDEX (°C)	MEAN HUMIDITY (%)	RAIN (mm)	EVAPO-TRANSPIRATION (mm)
2004	15.04	3	27.48	40	20.93	61.26	337	n/a
2008	15.01	4	27.42	40	21.14	64.25	623	612
2009	15.08	2	27.20	40	20.78	57.82	653	934
2010	15.12	-1	27.06	43	20.82	60.98	824	768
2011*	14.52	4	26.66	39	20.06	59.25	704	302

* 2011 data excludes 32 days.

3.2.2 Precipitation

Weather station data during the study period of 2009 -2010 are consistent with observations by Cowling et al. (1997) and Low et al. (1996). Weather station data for 2005, 2006 and 2007 were not included in the study because the weather stations were not calibrated. For the remainder of the study, Wireless Vantage Pro2™ weather stations (Davis Instruments, Vernon Hills, IL USA) were used to collect data shown in Table 2.1.

Rainfall fluctuations directly influence both vegetation distribution and composition (Tainton, 1999). Most importantly, the dry winter period between June and late August promotes conditions for natural veld fires. The majority of annual rainfall occurs during the wet summer months of late October to April. Rainfall distribution patterns during the study period are depicted in Figure 2.3.

3.3 Geology and soil

The parent material of the Conservancy is mainly composed of metamorphic migmatite rock with a distinct granitic color (Blatt et al., 1996). A high-gradient granite ridge runs from the southwest corner to the northwest corner of the Cordier Conservancy, encompassing 850 ha. Low et al. (1996) characterized the Mixed-Sour Bushveld (also referred as the Mooketsi Valley Plain landform) as a landform underlain with sandstone, granite and quartz covered by a very shallow layer of sand. As a result, soils in the Conservancy are poorly drained and are prone to erosion due to sloping topography. In highly eroded areas, exposed parent material is the dominant surface feature with intermittent clusters of trees along small escarpments where rain water is dammed for wild game.

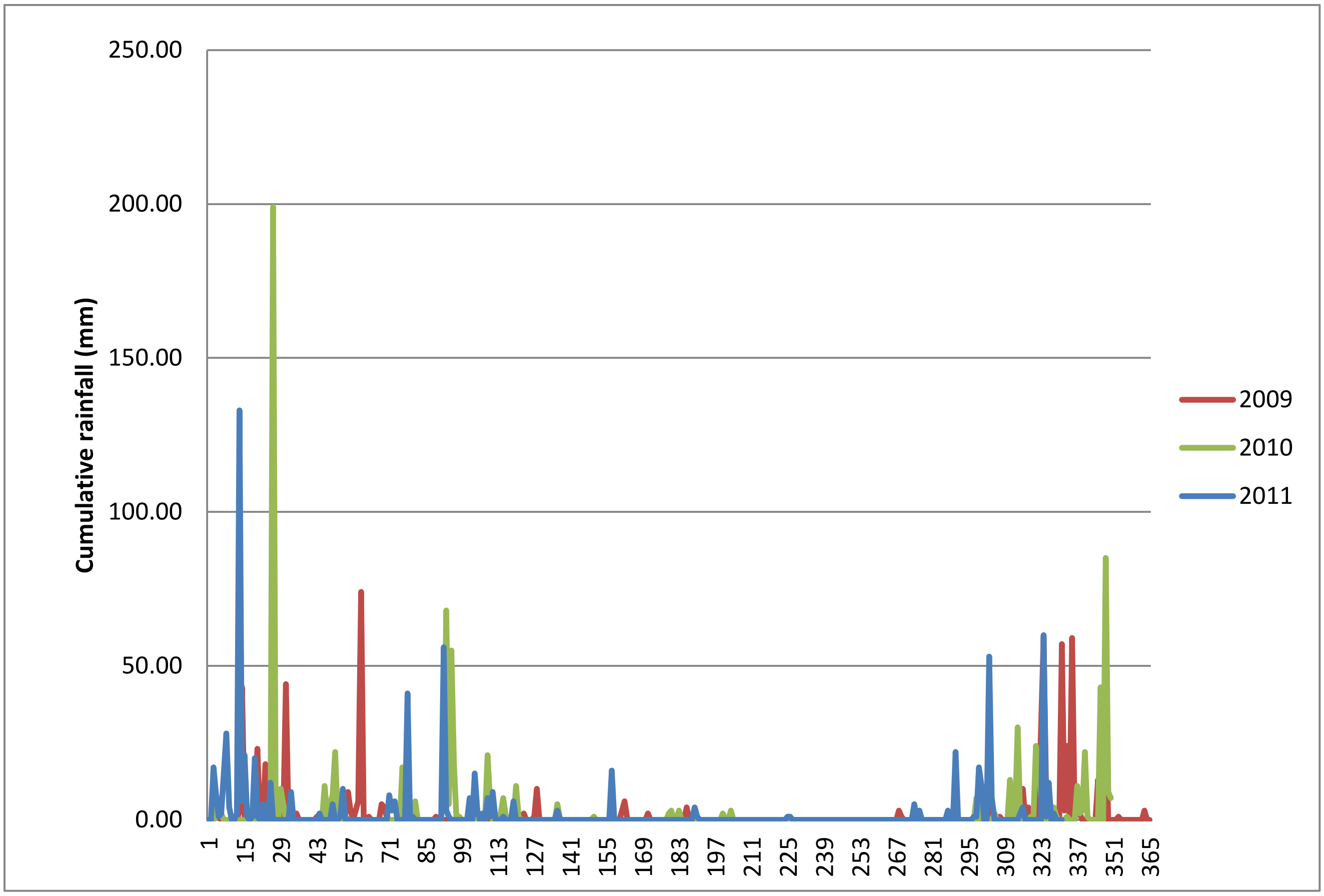


Figure 2.3 Rainfall distribution per day for years 2009, 2010 and 2011

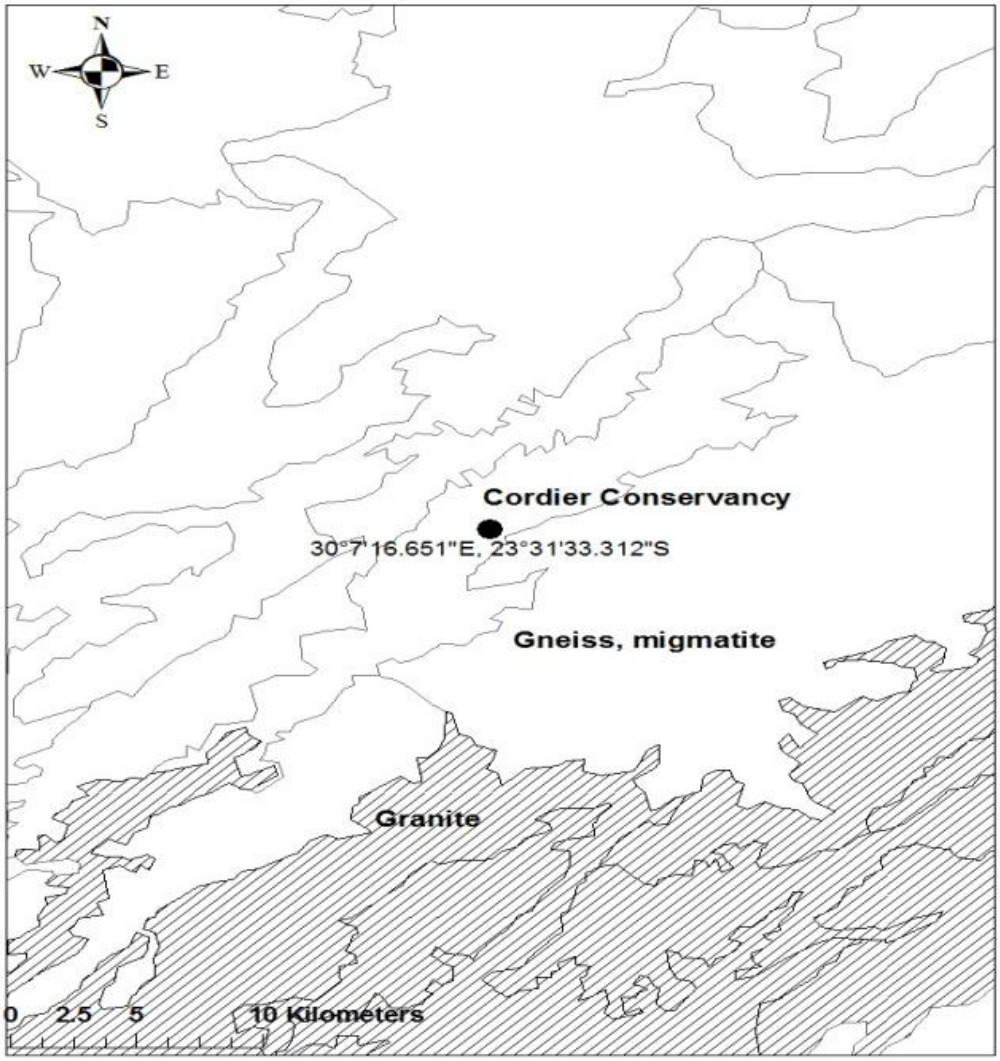


Figure 3.4 Geology of Cordier Conservancy

The Soil and Terrain database for South Africa (SOTER, 2008), at a 1:1 M scale, categorizes the area of the Cordier Conservancy as a eutric regosol (World Reference Base) (Bridge et al., 1998), analogous to the orthent entisols in the United States Department of Agriculture soil taxonomy (USDA Soil Survey Staff, 2010). These soils have a characteristically shallow ochric horizon comprised of low-coherence matrix material upon unweathered parent material (Batjes, 2004). Ultimately, eutric regosols have low water holding capacity, are susceptible to crusting and have low organic matter contents.

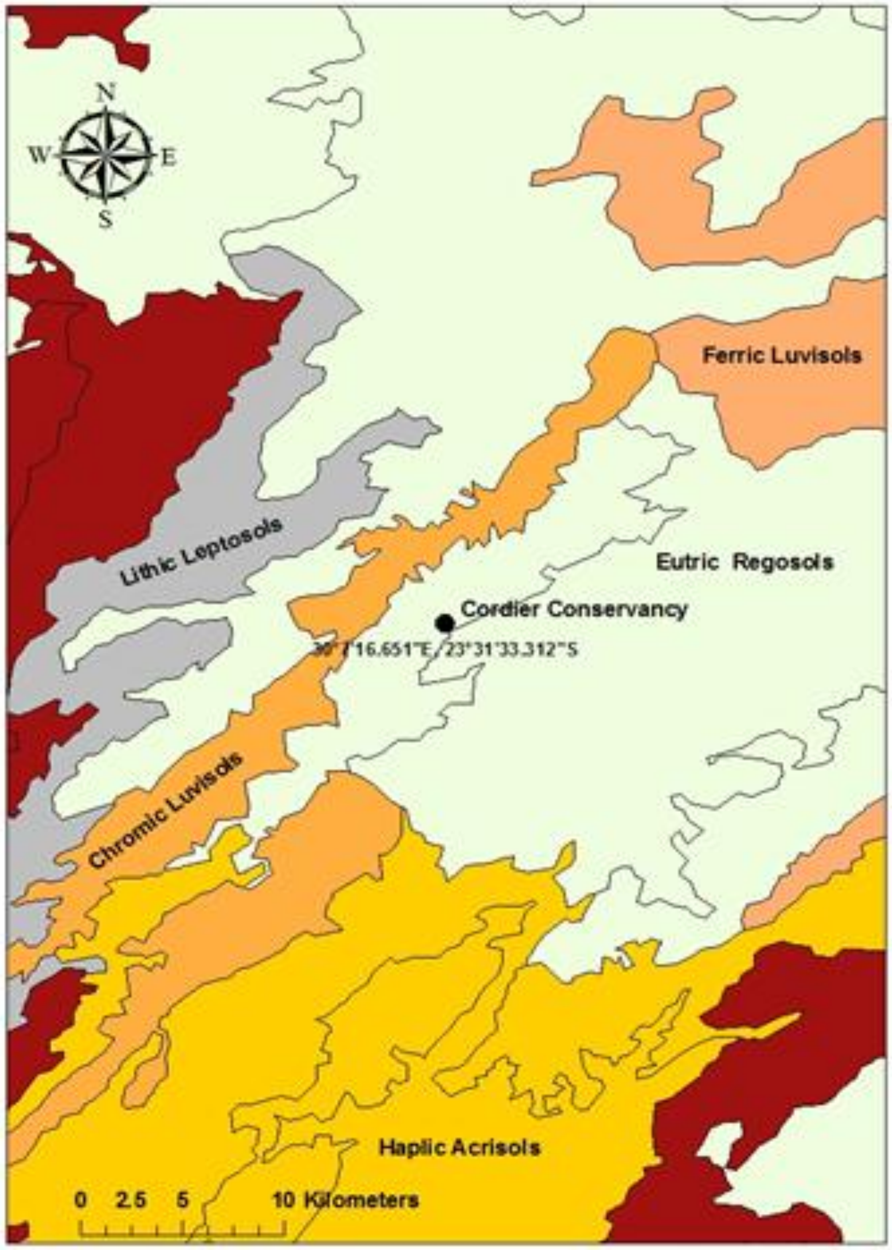
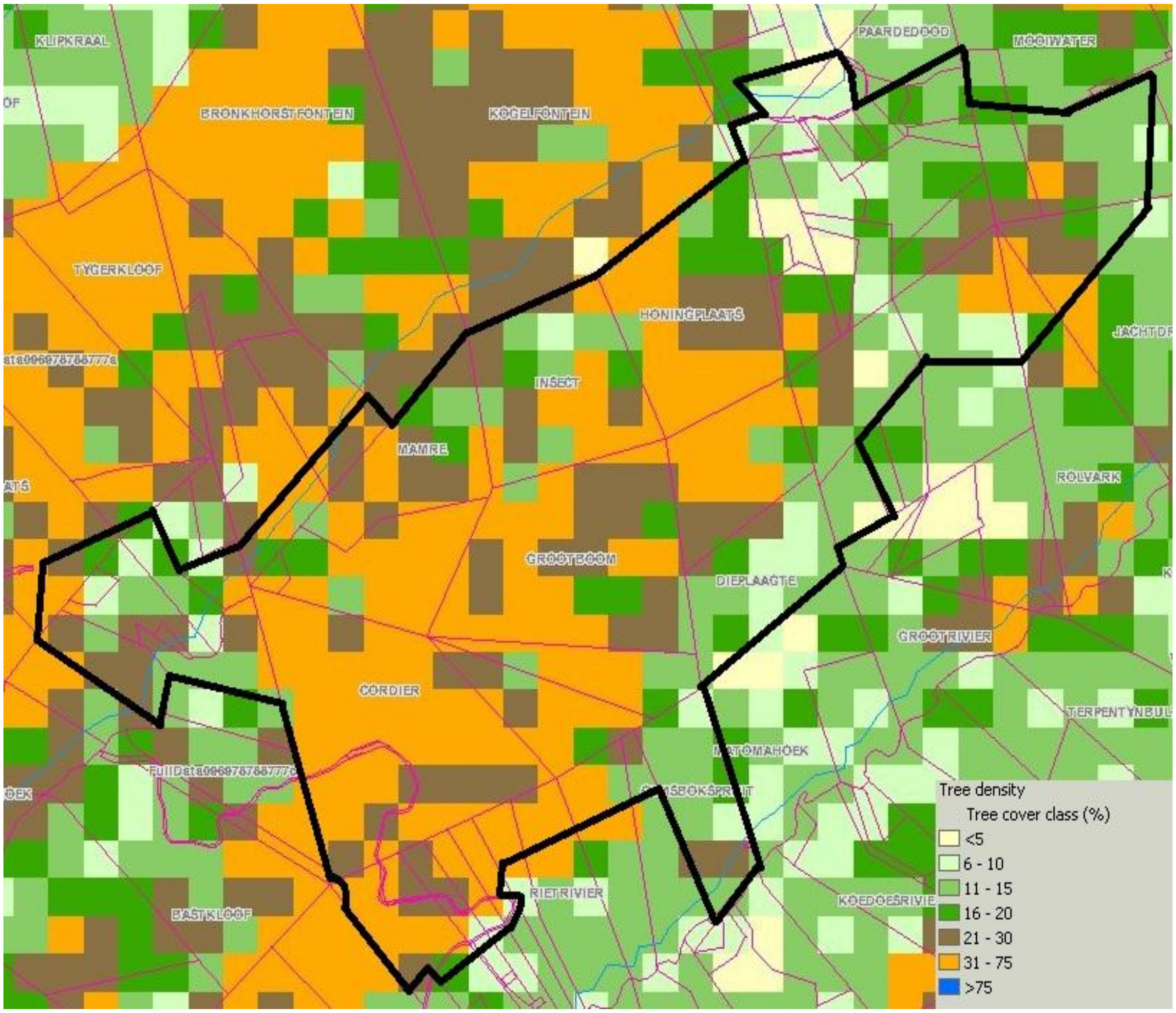


Figure 3.5 Soil taxonomy of Cordier Conservancy

3.4 Vegetation

The botanical composition of the Mopaneveld is dominated by *Colophospermum mopane*, several *Acacia* species (mainly *A. tortilis*, *A. mellifera*, and *A. nigrescens*), and intermixed *Combretum* species (Wild and Fernandes, 1968; Low et al. 1996). Grass composition varies as disturbances from fires, wildlife, and human activity influence species composition and disrupt ecological functions. Herbaceous production has been described as "sour" due to low primary productivity, high bush density, heavy grazing, and accelerated soil erosion that lower the nutritive value of the grasses (Mentis and Seijas, 1993). Figure 2.6 depicts the density of encroaching trees taken from the Agricultural Geo-Referenced Information Systems for South Africa (2007) in the Cordier Conservancy. A majority of the conservancy has at least 35 - 75% tree cover.

Sankaran et al. (2005) postulate that fire in a semiarid savannah is not the main driver of observed biome changes. Rather, erratic precipitation patterns and herbivore activities are the main determinants of changes in savannah vegetation and structure. These two factors contribute to the loss of canopy cover that in turn increases erosion and favours less palatable woody vegetation instead of more palatable herbaceous vegetation (van de Koppel and Rietkerk, 2000). In time, less palatable woody, pioneer species encroach on disturbed areas, leading to a loss of biodiversity.



http://www.agis.agric.za/agismap_atlas/AtlasViewer.jsp?MapService=agis_atlas2006&ProjectId=6&LId=0&OId=0

Figure 3. 6 Tree density of Cordier Conservancy

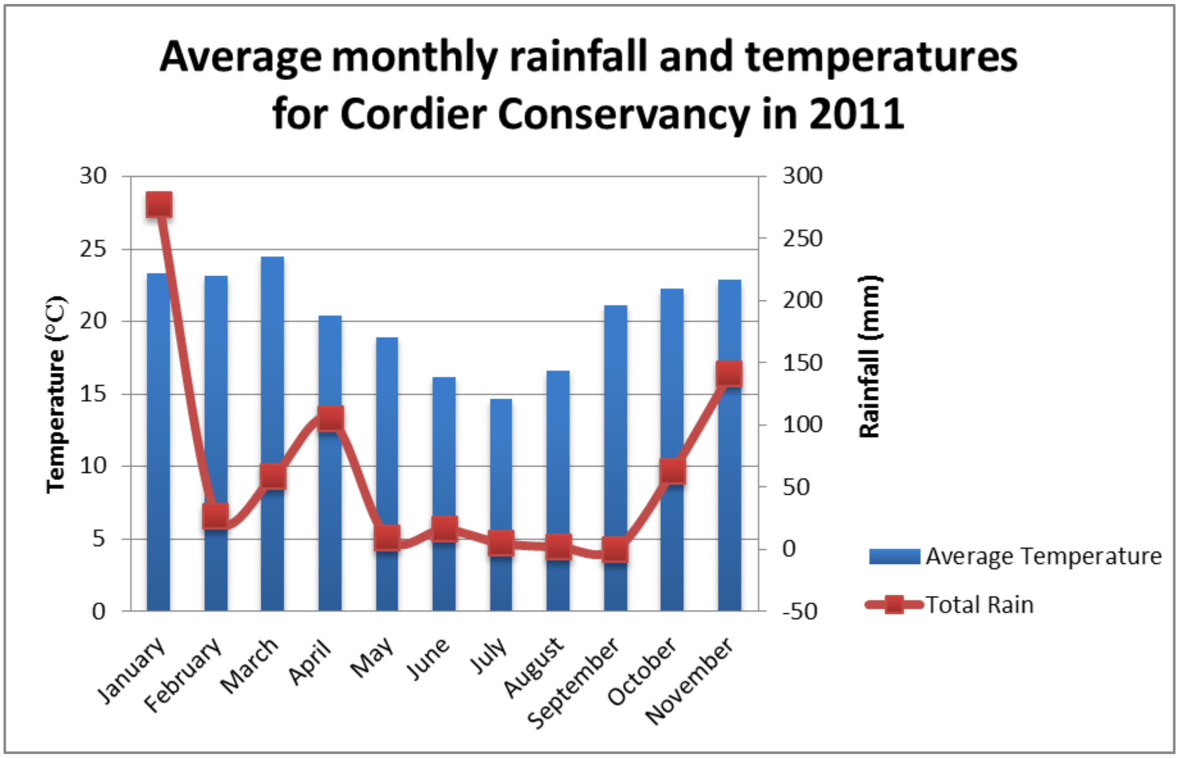


Figure 3.7 Relationship between temperature and rainfall in 2011

Private ownership of large areas in and near the Mopane savannah have further disrupted migratory patterns of wildlife, isolated critical resources, and burdened a fragile ecosystem with extensive agricultural operations and intensified cattle grazing. At the end of apartheid in 1994, 87% of all agricultural land was owned by white farmers, with only 12% owned by blacks (Kargbo, 2006). The South African statistical agency (Statistics South Africa, 20011) showed that by 2002, almost 70% of the total land area in Limpopo was owned by large, white-owned commercial agricultural enterprises. Small holders, who farm roughly the remaining 30% of the land, represent the majority of the population, while the white population comprises only 2.4%. Row and Rebelo (1996) suggested that the Mopaneveld has a low agricultural productivity potential, and therefore has remained relatively intact with 38% of the total land area under wildlife conservation. New approaches combined with technological breakthroughs have allowed for improved ecological assessments and monitoring. The SANBI (2010) report contradicts the total percentage of land under conservation in this region because the new classification system ordains the Cordier Conservancy as an ecosystem separate from the Mopaneveld to that of the Tzaneen Sour Bushveld.

3.5 Fauna

As a wildlife conservancy, the Cordier is a managed ecosystem supporting over 2,500 head of game. Careful monitoring of its biological condition is necessary to sustain the carrying capacity of both grazing and browsing ungulates. The economic viability of the Cordier Conservancy depends on maintaining herds of trophy game, and therefore vegetation and other ecosystem services are required for sustainability. A list of wild game herds during the beginning of this study in 2009 is given in Table 4.2.

Table 3.2 Herd count and value of Cordier Conservancy wildlife in 2009

Species (local name)	Scientific name	Herbivory*	Total number	Value per animal (Rand)	Total value of herd (Rand)
Blesbok	*Damaliscus pygargus phillipsi*	Grazer	20	529.10	10,613.75
Blue wildebeest	*Connochaetes taurinus*	Grazer	226	1135.55	256,918.19
Bushbuck	*Tragelaphus scriptus*	Browser	163	2681.90	436,720.60
Bushpig	*Potamochoerus larvatus*	Grazer	26	42.25	1,096.81
Common Duiker	*Sylvicapra grimmia*	Browser and Grazer	74	1032.20	76,733.75
Eland	*Taurotragus oryx*	Browser	58	3486.60	200,479.50
Giraffe	*Giraffa camelopardalis*	Browser	15	7255.95	108,476.45
Impala	*Aepyceros melampus*	Browser and Grazer	796	180.05	143,364.81
Kudu	*Tragelaphus strepsiceros*	Browser	369	1686.10	621,749.38
Klipspringer	*Oreotragus oreotragus*	Browser	18	2925.00	51,772.50
Mountain Reedbuck	*Redunca fulvorufula*	Grazer	30	1890.85	55,780.08
Nyala	*Tragelaphus angasii*	Browser	34	3583.45	122,625.66
Steenbok	*Raphicerus campestris*	Browser	48	855.40	41,384.25
Warthog	*Phacochoerus africanus*	Grazer	426	202.15	86,111.86
Waterbuck	*Kobus ellipsiprymnus*	Grazer and Browser	124	3139.50	388,513.13
Total			**2426**		**2,602,340.70**

* IUCN. (2008). IUCN Red List of Threatened Species. Version 2011.2 (http://www.iucnredlist.org/)

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CHAPTER 4: HARVESTING ENCROACHING BUSH BIOMASS FOR BIOCHAR PRODUCTION IN THE MOPANE SAVANNAH

4.1 Abstract

The feasibility of producing bush-derived biochars from a bush-encroached savanna in the Province of Limpopo was investigated. In this study, the biological condition of a degraded savannah was assessed through botanical composition surveys of herbaceous and non-herbaceous cover, soil sampling, weather monitoring, woody biomass community structure assessment, and resource health indicators to determine the ability of the reserve to sustain present wildlife herds. From these annual assessments, two native encroaching tree species were selected for biochar production due to their high densities, robust abilities to survive fire girdling, and for their ethnographic value to local villages. The characterization of bush-derived biochars included proximate, ultimate and chemical analyses at different production temperatures using two pyrolytic stoves. After 20 months of hand thinning by local wood harvesters, highly palatable herbaceous cover responded positively to thinning of select tree species.

4.2 Introduction

Several million hectares of South African land that was historically savannah are now encroached by bush. Bush encroachment significantly reduces forage productivity and palatability, and lowers the carrying capacity of lands managed with wildlife. Bush-derived biochar, prepared from encroaching species, is a practical means of recapitalizing soil carbon (C) stocks, while also being a catalyst for restoring soil nutrient cycling and increasing nutrient retention. The recapitalization of soils with recalcitrant C can improve the fertility of small holder farmer plots and provide viable by-products that generate income and increase ecosystem resilience. Labile carbon (non-recalcitrant C) in Mooketsi Valley soils is short-lived as decomposition rates of soil organic matter prevent carbon accrual. As soil C stocks decline, the ability to retain water and hold nutrients decreases dramatically. Bush-derived biochar can improve soil health and recapitalize ecosystem functions. I investigated whether selective culling of trees and shrubs in encroached savannah land would lead to improvements in browse for wildlife on the one hand and whether biochar made from the culled wood could be incorporated into the soil to help reverse years of soil degradation.

An integrated biochar system could be used to reverse environmental degradation, increase yield and improve resource use efficiency. Combustion of fuel wood in biochar cook stoves, with culturally appropriate designs, could improve fuel use efficiency, indoor air quality and produce biochar for soil amelioration (Joseph et al., 2009; Whitman et al., 2011). An integrated biochar system could provide for shared stewardship of these fragile environments by using agroecological principles to minimize human impacts and restore biodiversity. Such a biochar system addresses one of the root causes of poverty - depleted soils at the household scale, while at the same time being a cost effective strategy for savannah rehabilitation and global climate change mitigation (Whitman et al., 2011).

4.3 Methods

4.3.1 Site selection

The Cordier Conservancy is located 23°30'12.72"S and 30° 9'25.27"E; approximately 84 km northeast of Polokwane, South Africa. Spanning 4,600 ha, the Cordier Conservancy is owned and operated privately as an ecotourism game reserve as well as a water catchment area for surrounding agricultural operations. The Cordier Conservancy was selected for study in 2010 in coordination with the land owner, ZZ2 Farms (Bertie van Zyl Pty. Ltd.), to investigate the viability of a pilot co-stewardship program wherein local villagers selectively harvest the encroaching tree species and sell them as firewood. This provides the socioeconomic benefits of money and fuel-wood for harvesters and serves as a means of thinning encroached areas in the Conservancy. The site is fenced and managed by professional hunters (certified PH) and game managers.

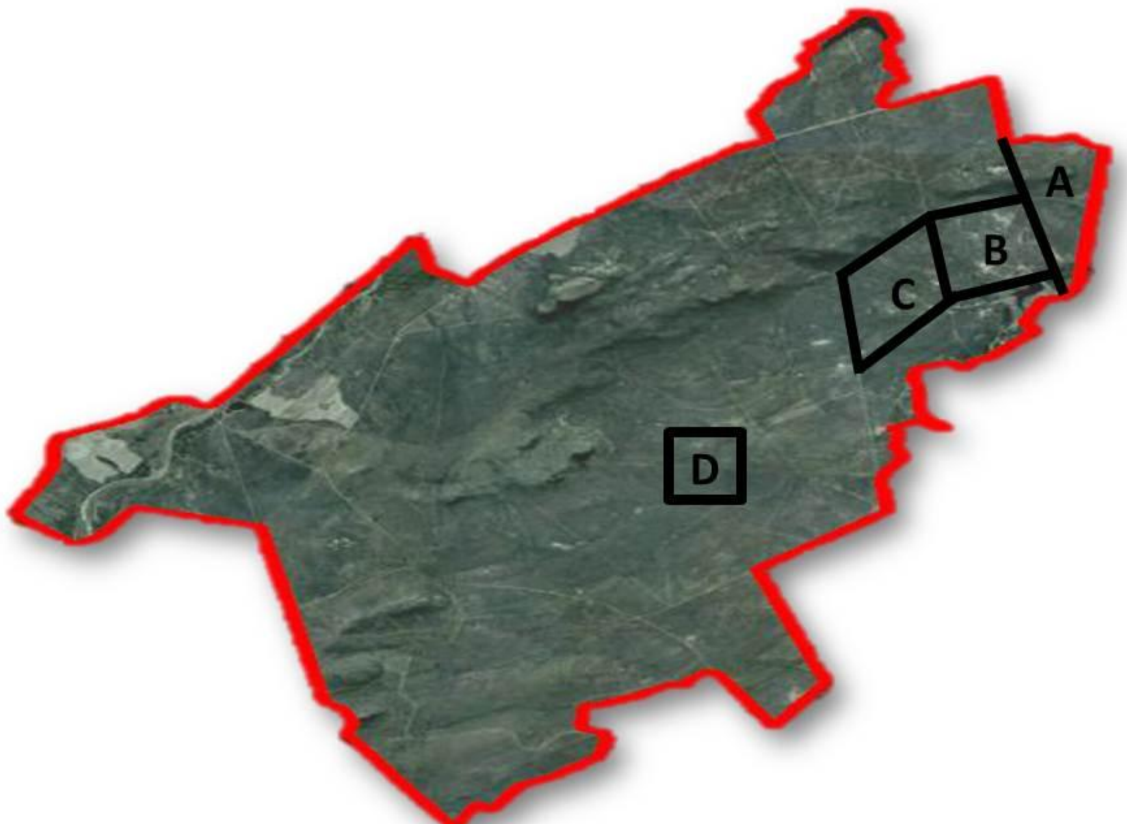


Figure 4.1 Experimental plot layout for Cordier Conservancy

4.3.2 Botanical composition survey

In order to monitor the ecological impacts of this project, two botanical composition surveys were conducted pre- and post-thinning treatments in 2011, during different seasons. In this unimodal climate, herbaceous and non-herbaceous cover is influenced by the seasonality of the short wet summer and long dry winter. This directly determines the balance between herbaceous and non-herbaceous species and sustenance for wildlife. In particular, environmental physiological factors can be correlated to the abundance of annual plant species.

The constraints of developing a scientifically appropriate method for sampling large areas are numerous; tree densities of thorny shrubs and trees, wild game, flooding and timing of fires all limit access. In this context, I adapted the classical vegetation ecology methodology of Braun-Blanquet (1932) to classify cover, density, and relative abundance of plant communities using the Barbour et al. (1987) sampling method, a plotless / transect line approach. The transect line crossed Blocks A, B and C (Figs.4.1 and 4.2), and spanned 2.86 km. A total of 9 samples were collected at 300 m intervals. Each transect quadrant was four m^2.

Supplemental botanical information was provided by ZZ2 Game Managers who conduct annual botanical appraisals for determining carrying capacity. The complete listing of identified graminoid and woody species from the 2009 ZZ2 resource inventory is given in Tables 4.4 and 4.5 in the Results section of this chapter.

4.3.2.1 Composition of herbaceous and non-herbaceous biomass

The composition of herbaceous and non-herbaceous biomass was studied using the aforementioned methodology. Cover, canopy level, abundance and density were determined for species along the transect line as instructed in the new Braun-Blanquet method (Braun-Blanquet et al., 1965; Wilken, 1978). Graminoid species were identified using the van Oudtshoorn (1999) guide, and non-herbaceous species using the guide by van Wyk and van Wyk (1997).

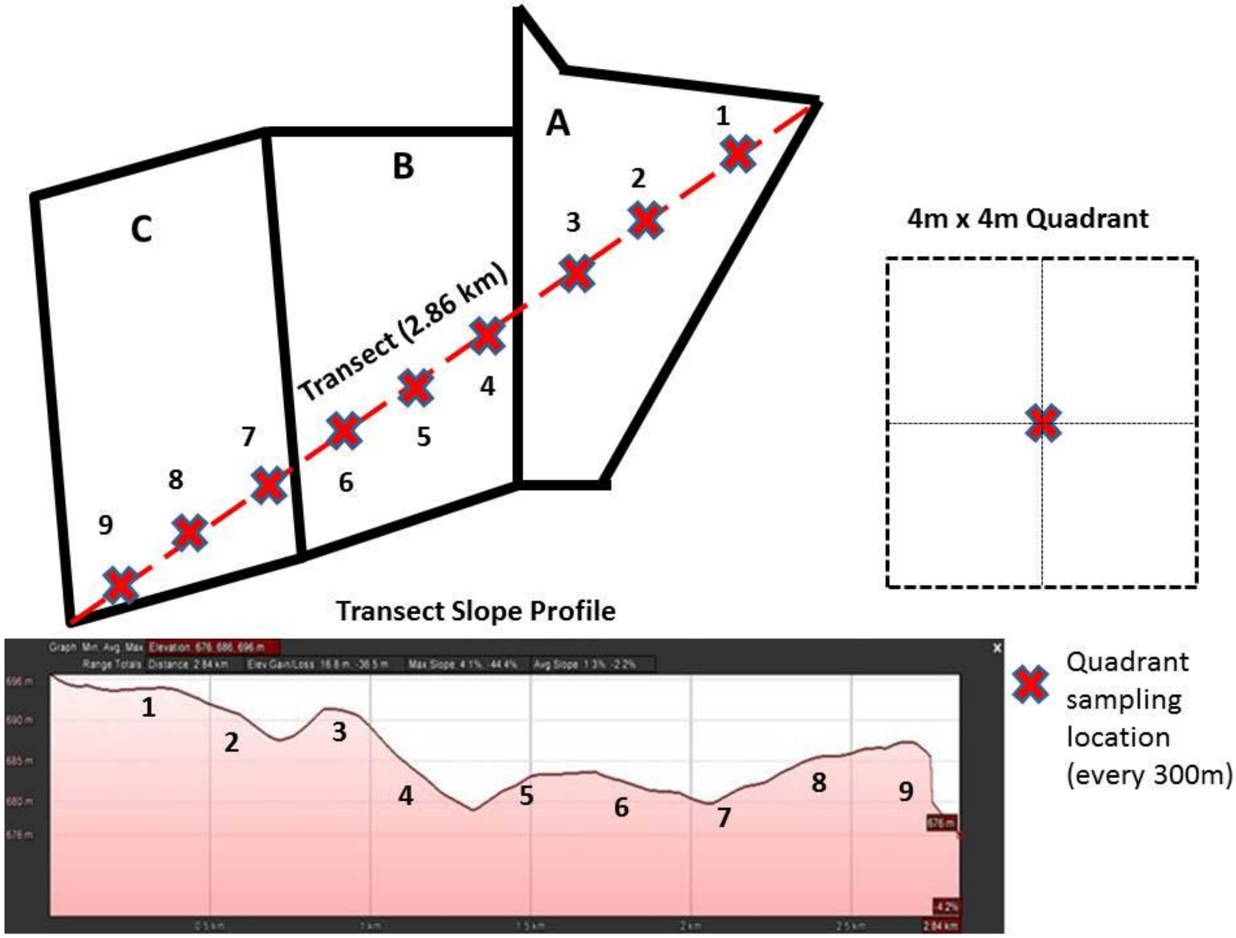


Figure 4.2 Transect and elevation profile of Cordier Conservancy

4.3.2.2 Chemical and polymer characterization of selected woody biomass

Results from botanical composition surveys revealed the abundance and location of encroaching species. A list of harvestable tree species was formulated to select encroaching tree species and prescribe a tree diameter-based limit on harvestable species per block. Trees with diameters less than 10 cm (approx. diameter of a 2 L plastic bottle) were allowed to be harvested, while larger, endangered and climax species remained. Two harvested tree species were collected for chemical analyses and sent to Bemlab (16 Van der Berg Crescent Gant's Centre Strand, Posbus

684 Somerset Mall, 7137). A mixture of both bark and trunk material were chipped to a thickness of 2 – 8 mm and then milled. Phosphorus (P, mg kg^{-1}), potassium (K, cmol kg^{-1}), calcium (Ca, cmol kg^{-1}), magnesium (Mg, cmol kg^{-1}), pH (water and KCl), CEC (mg kg^{-1}), and percent Ca, Mg, P and K were analyzed.

To illuminate how feedstocks can affect biochar quality, selected tree species were analyzed for *in vitro* digestibility (IVD) and cellulose, hemicellulose and lignin contents. Carbon density and aromaticity are important attributes of a good biochar, and therefore woody feedstocks are preferable as they result in biochars with increased aromaticity at lower temperatures and are less thermally labile (Kercher and Nagle, 2003; Downie et al., 2009; Brewer et al., 2011). Without an international standard for biochar classification, assays chosen were guided by the latest draft of proposed methods for characterizing biochars (IBI, 2010). In doing so, chemical and polymer content of feedstocks were characterized before thermal conversion to biochar. Neutral detergent fiber (Engels et al. 1967, Tilly et al. 1963), acid detergent fiber (Goering and Van Soest, 1970) and acid detergent lignin (Goering and Van Soest, 1970) were determined for each sample.

4.3.3 Veld condition

Veld condition was determined by combining botanical surveys and ecological status of species within sampling areas. Ecological status of grasses was measured according to van Oudtshoorn (1999) and assigned to five categories: "decreasers", which are palatable climax grasses that decrease in abundance as degradation severity increases; "increaser I" are unpalatable climax species usually found in an underutilized veld; "increaser II" are grasses commonly found in over-grazed savannahs and are usually robust pioneers that can establish quickly; "increaser III" are unpalatable, dense climax grasses found in very poor conditions and are highly competitive when grazed; and "invaders", which are non-indigenous grasses. Grasses were also categorized by plant succession stage and grazing value. Plant succession stages comprised three categories: pioneer, subclimax, and climax. Grazing values of grasses ranged from 1 – 3, with 3 being the most palatable; 2, where palatability is subject to vegetative stage or condition; and 1 being unpalatable (van Oudtshoorn, 1999).

Veld condition was also determined according to the scheme of van Wyk et al. (1997) that classifies grasses according to their ecological status or as "biological indicators." Different from the aforementioned five categories, the authors correlated abundance of species with the relative condition of the veld described as poor or rich.

4.3.3.1 Soil sampling

During the winters of 2010 and 2011, soil samples were collected in eight partitioned blocks according to the Cornell Soil Health Manual (Gugino et al., 2009) soil sampling protocol. A total of 20 samples were collected from the top 15 cm of soil from each block using a soil auger. Grid designs were adapted from existing road networks within the project site. Each block varied in area as a result of accessibility, firebreaks, and on-going harvesting activities. Each sampling coordinate was recorded using a Garmin E-Trek H for re-sampling in the same location the following year. Intra-block sampling patterns (Figure 4.3) were performed according to Gugino et al. (2007). All samples were sent to ZZ2 Laboratories (Private Bag 1106, University of Limpopo, Sovenga, South Africa, 0727) for analysis. Chemical analyses for sampled soils (Table 4.2) were outsourced to BemLab (Somerset Mall, Pretoria, South Africa). These included: pH in 1N KCl; resistance (ohms); inductively coupled plasma atomic emission spectroscopy (ICP-AES) was used to determine cation contents (Na, K, Ca, Mg) extracted with ammonium acetate (pH 7), trace elements (Zn, Mn, Cu, Fe) extracted with disodium EDTA, H extracted with potassium sulfate (Eksteen, 1969), B extracted with hot water, and P extracted with ammonium fluoride in HCl (Bray and Kurtz, 1945), C was determined by oxidation (Walkley and Black, 1934); CEC was determined by extracting in 0.2 N K_2SO_4; NH_4-N was determined by automatic flow injection analysis system; particle size was determined by the hydrometer method (Day, 1965).

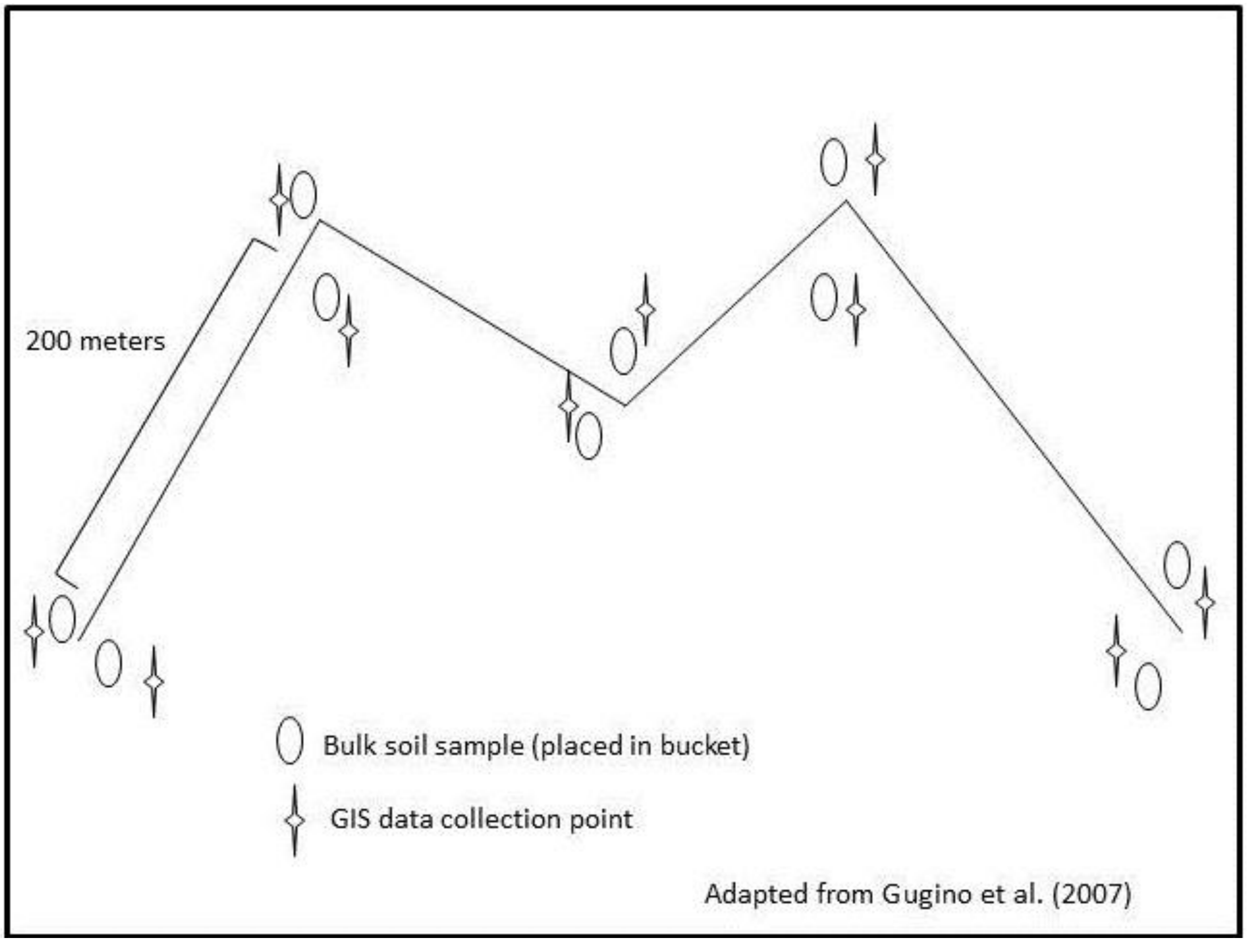


Figure 4.3 Soil sampling design within blocks

Soil from blocks A, B and C was sampled in January, 2010. Block D was not sampled in 2010 because of the thinning activity going on at that time. All blocks were sampled in January, 2011. The size and management history of each block are given in Table 4.1.

Table 4.1 Management history and area of blocks A, B, C and D

Block label	Area (ha)	Latest fire (yr)	Last thinned (yr)
A	110.93	2008	2009
B	123.48	2010	2010
C	151.69	2010	2010
D	42.71	2009	2010

4.3.3.2 Browse quality

Browse quality was determined as the palatability of tree forage with a range of 1 – 3, according to van Wyk and van Wyk (1997), with 3 being the most palatable. Species recorded in the botanical surveys were cross-checked with existing Red Lists for invasiveness status (IUCN, 2011).

4.3.3.3 Biochar characterization

Bush-derived biochars were characterized according to the International Biochar Initiative Draft (2010). I adapted these recommended methods that included proximate and ultimate analyses. Riley (2007) extensively explains and has set the standards for characterizing charcoal.

Proximate analysis of charcoal includes inherent moisture content, ash content, volatile matter, fixed carbon and total sulfur content. Ultimate analysis measures C, H, N and O content of each sample. Biochars sent to Advanced CoalTechnology (ACT) Labs (Pretoria, South Africa) were characterized for both proximate and ultimate analyses. Samples were analyzed by Bemlab for pH (water and 1 N KCl) and CEC.

In addition, I conducted chemical analyses on each biochar produced to determine pH and CEC. Methods used to characterize biochar samples (Table 4.2) were those used by Advanced Coal Technology (ACT, Wierda Park South, South Africa 0057) to characterize coal samples.

Table 4.2 Methods employed by ACT to characterize biochar

Item	**Procedure / Method**
Sample preparation	ACT-TPM-001 ISO 13909-4:2001
Moisture content (%)	ACT-TPM-010 SANS 5925: 2007
Ash content (%)	ACT-TPM-011 SABS ISO 1171: 1997
Volatile matter content (%)	ACT-TPM-012 SABS ISO 562: 1998
Total sulfur via IR spectroscopy (%)	ACT-TPM-013 ISO 19579
Ultimate analysis	ISO 12902 - CHN Instrumental method

4.4 Feedstock selection for biochar production

In 2009, ZZ2 Game Managers composed a list of trees species to be either harvested or protected (Table 4.3). Limiting harvests to smaller diameter trees permitted hand harvesting to be effective while simultaneously preventing erosion and sustaining browse for wildlife.

Table 4.3 Harvestable tree species list

Family	Binomial name
Anacardiaceae	*Rhus lanceae*
Cekastraceae	*Gymnosporia buxifolia*
Combretaceae	*Combretum apiculatum*
	Combretum erythrophyllum
	Combretum hereroense
	Combretum molle
	Combretum zeyheri
	Terminalia prunoides
	Terminalia sericea
Fabaceae	*Acacia mearnsii*
	Albizia anthelmintica
	Burkea africana
	Colosphospermm mopane
	Dichrostachys cinerea
	Peltophorum africanum
Malvaceae	*Dombeya rotundifolia*
Olacaceae	*Ximenia caffra*
Proteaceae	*Fuarea saligna*
Rhamnaceae	*Ziziphus mucronata*
Sapindaceae	*Papea capensis*

4.4.1 Selection criteria for thinning

Density and successional patterns of encroached bush were key criteria for locating thinning sites. Blocks A, B, C and D had an estimated 3000 hectares with 5 - 18 kg m^{-2} biomass. An open savannah has a biomass load of 1.2 – 2.3 kg m^{-2} (Tucker et al., 1985; Levine, 1991). Excessive tree growth is evidence of a biome transition from a savannah to woodland; therefore, trees were selected to reduce woody biomass load and increase herbaceous cover. Thinning was started in block A in 2009, because of proximity to the access road where harvesters entered and exited. Thinning activity followed a chronosequence from block A to block D during a nine month period ending in August, 2010.

4.5 Biochar production

Pyrolysis of feedstocks was performed in two, homemade, indirect pyrolytic stoves. One stove was fabricated as a research stove (Appendix A) and the other was a representative of a locally designed clay pyrolytic stove. The research stove included a thermo-electric fan to increase natural draught and was constructed from aluminum. Both stove designs were adapted from the Anila stove (Ravikumar, 2008). Biochars were produced at 300°C, 350°C and 450°C.

4.5.1 Thermodynamic analyses

Heat transfer between the inner, direct combustion chamber and the pyrolytic chamber were measured using two Type K thermocouples with an EA15 EasyView Dual Input Temperature Data Logger (Extech, Nashua, NH USA). The data logger recorded readings at 60 second intervals. The direct combustion thermocouple was located 30 cm below the lid on the surface of the outer direct combustion chamber wall. The second thermocouple was placed 30 cm below the lid but on the outer wall of the pyrolytic chamber.

Biochar yield (**η_{fc}**) was calculated using the following formula (Riley, 2007):

$$\boldsymbol{\eta_{fc} = (m_{char} / m_{bio})[c_{fc} / (1 - b_a)] \times 100}$$

m_{char} = dry mass of biochar from the kiln

m_{bio} = dry mass of biomass loaded into the kiln

c_{fc} = fixed C content of biochar as measured by ASTM Standard D 1762- 1984

b_a = ash content of the dry biomass

4.6 Results

Research conducted at the Cordier Conservancy began in January, 2010, and was completed in August, 2011. Results from the first stage of the Cordier Conservancy project showed a dynamic regrowth of herbaceous cover and improved veld conditions after hand thinning in selected plots. Though 20 months are insufficient to demonstrate long-term restoration, observable improvements were documented and are described and discussed in this section.

4.6.1 Botanical composition

Herbaceous and non-herbaceous species were identified in nine quadrants and were classified according the new Braun-Blanquet method (1965). Braun-Blanquet (1932) is the standard method used for conducting coverage – abundance vegetative assessments.

Additionally, invasiveness status, browse and graze quality were attributed to each species. Results from the 2009 ZZ2 resource inventory are given in Table 4.4. Fabaceae and Combretaceae were the most abundant families of the 23 identified, representing 36.4% of total woody species.

Grasses were categorized similarly to woody species, with the exception of ecological health (veld condition), plant succession stage, and grazing status (Table 4.5). Twenty-one grasses were identified in nine quadrants. Of the 21 grasses identified, 15 were indicators of a poor-veld with pioneer and subclimax species dominating the plant succession stages. In total, the majority of grasses (67%) were "increaser" species, while the remaining 33% were classified as "decreasers". Seven grass species were identified as "decreasers." These results indicated a veld in poor condition with a higher abundance of unpalatable grasses that, without proper management, will out-compete the highly palatable "decreaser" grasses.

Table 4.4 Scientific names of trees in the Cordier Conservancy, their invasiveness status, and their browse quality.

Scientific name	Family	Status*	Harvested	Browse quality**
Acacia spp. (mearnsii)	Fabaceae	Invasive	+	1
Albizia spp.	Fabaceae	Not invasive	+	3
Aloe spp.	Xanthorrhoeaceae	Not invasive	-	1
Berchemia spp	Rhamnaceae	Not invasive	-	3
Boscia albitrunca	Capparaceae	Not invasive	-	3
Boscia foetida	Capparaceae	Not invasive	-	1
Brachylaena huillensis	Asteraceae	Not invasive	-	1
Burkea africana	Fabaceae	Not invasive	+	1
Carissa spp	Apocynaceae	Not invasive	-	1-fruit
Celtis africana	Cannabaceae	Not invasive	-	2
Colosphospermum mopane	Fabaceae	Not invasive	+	3
Combretum apiculatum	Combretaceae	Not invasive	+	3
Combretum erythrophyllum	Combretaceae	Not invasive	+	2
Combretum hereroense	Combretaceae	Not invasive	+	3
Combretum imberbe	Combretaceae	Not invasive	-	3
Combretum molle	Combretaceae	Not invasive	+	3
Combretum zeyheri	Combretaceae	Not invasive	+	3
Commiphora spp.	Burseraceae	Not invasive	-	3
Croton spp.	Euphorbiaceae	Not invasive	-	3

Cussonia spp.	Araliaceae	Not invasive	-	3
Dichrostachys cinerea	Fabaceae	Not invasive	+	3
Diospyros mespiliformis	Ebenaceae	Not invasive	-	1-fruit
Dombeya rotundifolia	Malvaceae	Not invasive	+	3
Erythrina lysistemon	Fabaceae	Not invasive	-	2
Euphorbia spp.	Euphorbiaceae	Invasive	-	1
Ficus spp.	Moraceae	Not invasive	-	2
Faurea saligna	Proteaceae	Not invasive	+	1
Gymnosporia spp.	Celastraceae	Not invasive	+	2
Kiggelaria africana	Achariaceae	Not invasive	-	1
Mimusops zeyheri	Sapotaceae	Not invasive	-	1-fruit
Ochna spp.	Ochnaceae	Not invasive	-	3
Olea capensis	Oleaceae	Not invasive	-	2
Papea capensis	Sapindaceae	Not invasive	+	3
Peltophorum africanum	Fabaceae	Not invasive	+	3
Prunus africana	Rosaceae	Not invasive	-	1-fruit
Rhus spp.	Anacardiaceae	Not invasive	+	3
Schotia brachypetala	Fabaceae	Not invasive	-	3
Sclrocarya birrea	Anacardiaceae	Not invasive	-	3
Spirostachys africana	Euphorbiaceae	Not invasive	-	1
Strychnos spp.	Loganiaceae	Not invasive	-	3

Terminalia prunoides	Combretaceae	Not invasive	+	3
Terminalia sericea	Combretaceae	Not invasive	+	3
Ximenia caffra.	Olacaceae	Not invasive	+	3
Ziziphus mucronata	Rhamnaceae	Not invasive	+	3

* Invasive and Alien Species Red List, Agricultural Geo-Referenced Information System (AGIS, 2007), accessed from www.agis.agric.za on [2011]

** adapted from van Wyk and van Wyk (1997). Palatability scale of 1-3, with 1 being the lowest/unpalatable; 2 intermixed/condition (palatable at early stages of development or palatable but produces few leaves); 3 the best palatability.

Table 4.5 Scientific names of grasses, invasiveness status, palatability, biological indication status, plant succession stages, and grazing status.

Scientific name of grasses	**Status***	**Palatability ****	**Veld-indicator*****	**Plant Succession**	**Grazing Status**
Aristida adscensionis	-	1	Poor	Pioneer grass	Increaser II grass
Aristida congesta	-	1	Poor	Pioneer grass	Increaser II grass
Chloris gayana	-	3	Rich	Subclimax grass	Decreaser grass
Cynodon nlemfuensis	-	3	Poor	Pioneer grass	Increaser II grass
Dichanthium annulatum	-	2	Rich	Subclimax/climax grass	Decreaser grass
Digitaria eriantha	-	3	Mainly rich	Climax grass	Decreaser grass
Digitaria velutina	-	2	Poor	Pioneer/subclimax grass	Increaser II grass
Elionurus muticus	-	1	Poor	Climax grass	Increaser III grass
Eragrostis curvula	-	2	Poor	Subclimax/climax grass	Increaser II grass
Eragrostis gummiflua	-	1	Poor	Subclimax grass	Increaser II grass
Eragrostis racemosa	-	3	Poor	Subclimax grass	Increaser II grass
Eragrostis superb	-	3	Poor	Subclimax grass	Increaser II grass
Eustachys paspaloides	-	3	Poor	Climax grass	Decreaser grass
Heteropogon contortus	-	2	Poor	Subclimax grass	Increaser II grass
Hyparrhenia cymbaria	-	2	Mainly rich	Climax grass	Increaser I grass
Melinis repens	-	2	Poor	Pioneer/subclimax grass	Increaser II grass
Panicum deustum	-	3	Mainly rich	Climax grass	Decreaser grass

Panicum maximum	-	3	Rich	Subclimax/climax grass	Decreaser grass
Panicum repens	-	3	Poor	N/A	Decreaser grass
Perotis patens	-	2	Poor	Pioneer/Subclimax grass	Increaser II grass
Pogonarthria squarrosa	-	1	Poor	Subclimax grass	Increaser II grass

* Invasive and Alien Species Red List, Agricultural Geo-Referenced Information System (AGIS, 2007), accessed from www.agis.agric.za on [2011]

** Palatability scale of 1-3, with 1 being the lowest/unpalatable; 2 intermixed/conditions (palatable at early stages of development or palatable but produces few leaves; 3 the best palatability. (Van, 1999)

During the second botanical survey in 2011, torrential rains flooded most of the Cordier Conservancy, including all experimental blocks. As a result, herbaceous cover consisted predominately of *Panicum maximum* and *Panicum repens* in the nine quadrants. Grass growth and density exceeded normal vegetative growth; grasses were 1.5 – 2 m tall with densities of 2.5 kg m^{-2}, with intermittent deciduous trees including *Mimusops zeyheri*, *Carissa spp*., *Prunus africana, Strychnos spp.*, and taller fine-leaved trees from the Fabaceae family. Residual P and N from harvested trees in the Fabaceae family may have contributed to vigorous herbaceous growth in thinned areas (Hagos and Smit, 2004).

4.6.2 Chemical and polymer characterization of tree species

Of the tree species on the harvesting list, two were selected to be feedstocks for biochar production. *Acacia mearnsii* and *Dichrostachys cinerea* were the most abundant, non-herbaceous species and were present in densities high enough to restrict access by wildlife. Chemical and polymer characterizations (Table 3.6) were compared with other non-herbaceous and herbaceous species used as biochar feedstocks. Of the species selected, *Dichrostachys cinerea* biochar had the lowest P content and the highest Ca content. Prior and Alvin (1986) attribute the higher Ca content (anatomically) to axial strands of chambered parenchyma cells. This could have corresponding effects on char quality, if temperatures exceed 370°C, which is the critical temperature for calcium carbonate to thermally decompose.

Table 4.6 Chemical composition of selected feedstocks

Feedstock	P (mg/kg)	K (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)	CEC (mg/kg)	pH KCl	Ca %	Mg %	P %	K %
Acacia mearnsii	205.7	9.48	11.85	8.09	11.27	4.8	0.39	0.08	0.04	0.23
Dichrostachys cinerea	50.64	5.41	11.5	7.42	15.93	5.6	1.15	0.09	0	0.15
Eucalyptus camaldulensis	128.96	4.22	7.45	2.89	19.77	4.7	0.1	0.02	0.01	0
Zea maize rests	1554.11	19.78	6.54	10.21	28.23	5.9	0.13	0.11	0.15	0.62
grass	1703.56	17.94	13.38	14.4	29.3	6.5	0.43	0.15	0.2	0.59
Pinus patula	74.94	2.2	4.58	2.3	20.73	4.3	0.08	0.01	0	0

Polymer characterizations of the same feedstocks revealed more about the C content of each feedstock (refer to Fig. 3.5). Particularly important, feedstocks with fewer thermally labile fibers (cellulose and hemicellulose) did not yield as much biochar. *Acacia mearnsii* and *Dichrostachys cinerea* had the highest lignin contents and had properties similar to those of *Pinus patula*.

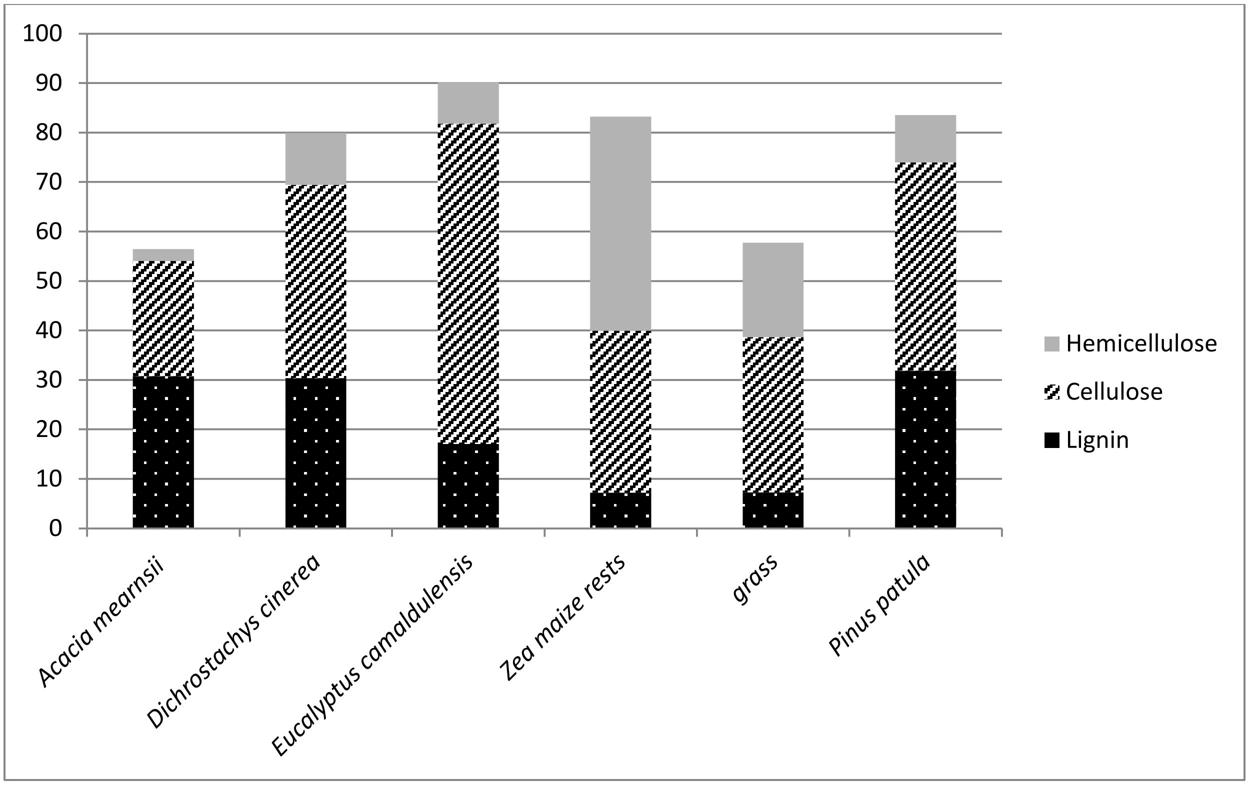


Figure 4.5 Polymer characterizations of selected feedstocks.

4.6.3 Soil chemical analyses

Soil sampling was conducted during two different seasons. Irrespective of block, soil texture was predominately sand with low pH, CEC, P and C. These data are in agreement with the SOTER soil mapping data for the Mooketsi region. The increase in soil P measured in 2011 could be attributed to different fire treatments on the selected blocks. I also sampled an adjacent tomato field to estimate the agricultural productivity potential of this soil, provided there are sufficient inputs of C, organic matter and fertilizers (see Table 4.7). Fire regimes implemented during the study period did not produce natural biochars in measurable quantities and did not improve C content in Blocks A, B and C. Reasons for this could be high fire temperatures that would produce more ash or subsequent rain events that could cause the char to erode from soil surfaces.

Table 4.7 Chemical analyses of soils sampled from blocks A, B, C and D.

Sample (block / year)	pH (KCl)	P Bray I	P Bray II	K	Exchangeable cations (cmol(+)/kg)				C
		mg/kg			Na	K	Ca	Mg	%
A 2011	4.2	3	51	82	0.10	0.21	1.21	0.48	0.31
B 2011	4.6	3	56	96	0.11	0.25	1.97	0.66	0.45
C 2011	4.0	1	37	77	0.09	0.2	1.24	0.96	0.31
D 2011*	4.0	2	49	65	0.10	0.17	1.26	0.52	0.43
A 2010	4.9	4	5	69	0.11	0.18	1.70	0.68	0.47
A 2010 HF	4.4	1	3	89	0.09	0.23	0.93	0.46	0.28
B 2010 LF	4.2	3	2	45	0.17	0.12	1.26	0.84	0.42
B 2010 WF	4.1	3	7	64	0.13	0.16	0.93	0.59	0.23
C 2010	4.8	3	5	95	0.12	0.24	1.85	0.63	0.57
Adjacent farm	6.5	234	605	356	0.18	0.91	5.76	1.52	1.14

** Block D was not sampled in 2010 because of thinning activity.

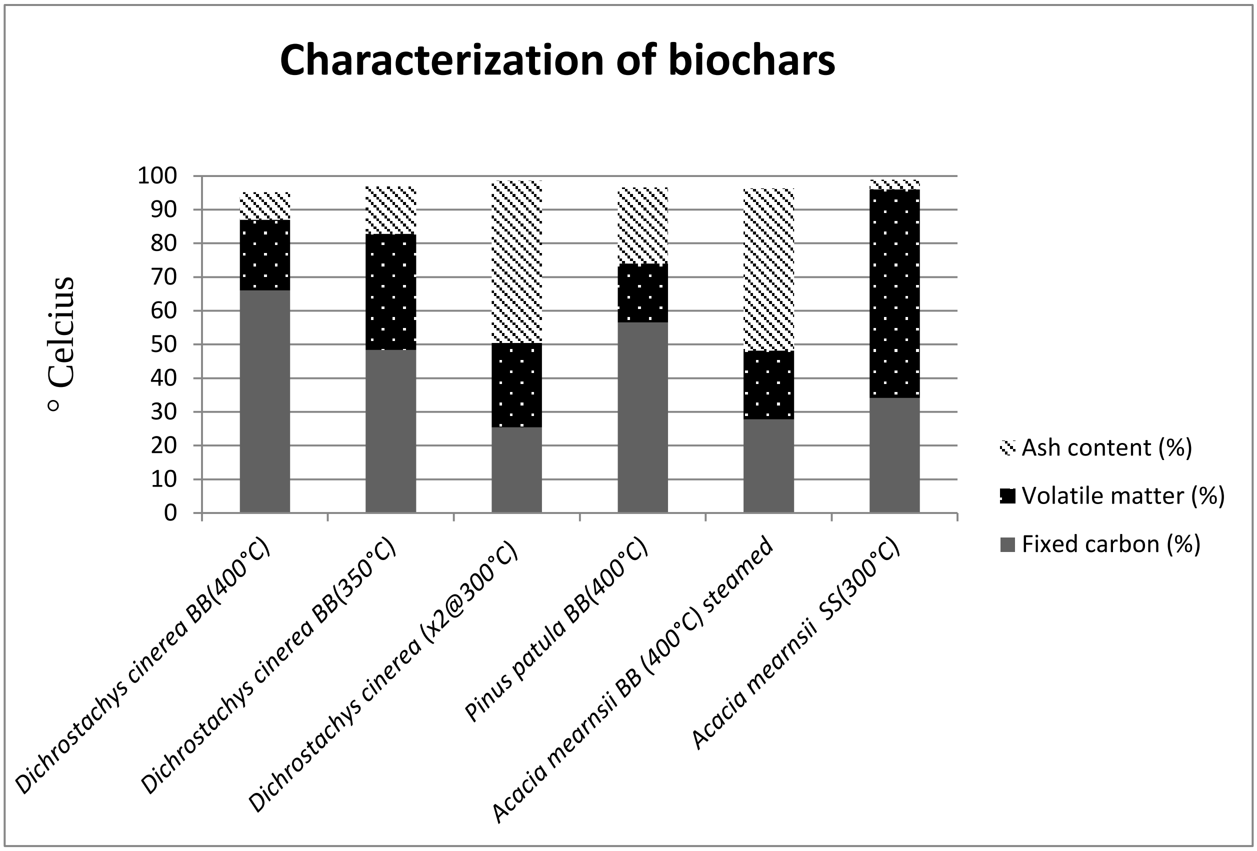
* B represents the southern end of blocks A and B.

HF hot fire (> 7 kg m^{-2}); LF low-intensity fire (2.5-5 kg m^{-2}); WF wet fire (< 2 kg m^{-2})

4.6.4 Biochar characterization

Without a published international standard for biochar characterization, the biochars produced were analyzed as coal for ultimate and proximate analyses. At the International Biochar Initiative Conference in Rio de Janeiro (September, 2010), Joseph et al. (2010), Cross et al. (2010) and Hayes et al. (2010) presented new methods and approaches for characterizing biochars and formulating an international standard feasible for use by small-holder farmers. However, ultimate and proximate analyses are expensive and laboratories capable of conducting these analyses are not available in most developing countries.

The relationship between volatile matter, fixed carbon, and ash content of *Pinus patula*, *Acacia mearnsii* and *Dichrostachys cinerea* at three production temperatures are shown in Figure 4.6. Complete analyses of the three feedstocks are given in Table 4.6.



* BB denotes aluminum research pyrolysis stove, SS denotes small clay pyrolysis stove

Figure 4.6 Characterization of bush-derived biochars

At lower pyrolysis temperatures, the volatile matter content was high, particularly in the biochar produced in the small clay stove. At higher temperatures, fixed C and ash content increased, regardless of feedstock (see Figure 4.7). Two treatments intended to "activate" the biochar were tested, but results were inconclusive. *Acacia mearnsii* BB (400°C) steamed was a biochar that had water applied after pyrolysis while the char was still hot. *Dichrostachys cinerea* BB (300°C) x2 was a char that was pyrolyzed twice as a result of incomplete pyrolysis during the first firing. This test was conducted to examine realistic potential outcomes of small-holder biochar production, if incomplete pyrolysis of feedstock occurs. Results indicate a higher ash content, but lower volatile matter and fixed carbon content for the double-charring experiment. Pyrolytic clay stoves do not reach sufficient temperatures to burn off volatile matter, and the composition of volatile matter resulting from these feedstocks is unknown. Spokas et al. (2011) found that slow pyrolysis (< 350°C) formed shorter C chains consisting of aldehydes, furans and ketones. Studies testing the effects of these compounds on either microbial populations or plant growth are limited. A few studies have shown lower seed germination and reduced plant growth when volatile compound contents are high (Kadota and Niimi, 2004; Deenik et al., 2010; Free et al., 2010). Generalizations are difficult, however, because different biochars produced from numerous feedstocks at varying temperatures under several production conditions were used. In future research, volatile organic compounds found on bush-derived biochars should be analyzed to determine their effects on agronomic potential and soil microbial activity.

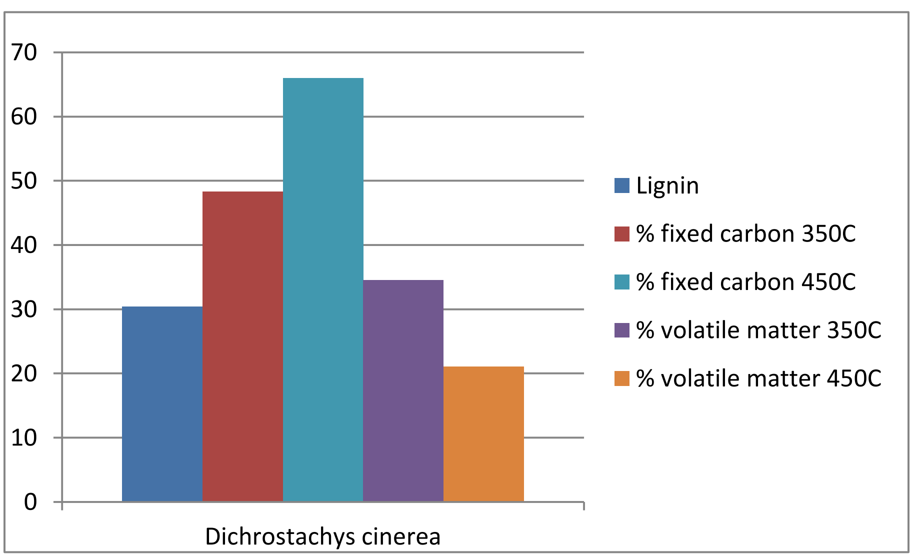


Figure 4.7 Comparison of fixed carbon and volatile matter at 350°C and 450°C of *Dichrostachys cinerea*

Table 4.7 Proximate, ultimate, and chemical analyses of biochars produced from *Pinus patula*, *Acacia mearnsii* and *Dichrostachys cinerea*

Sample identification	***Dichrostachys cinerea* BB(350°C)**	***Dichrostachys cinerea* BB(450°C)**	***Dichrostachys cinerea* Aug. (x2@300°C)**	***Pinus patula* BB(400°C)**	***Acacia mearnsii* BB (400°C) steamed**	***Acacia mearnsii* SS(300°C)**
Proximate analysis						
% inherent moisture content	6.8	6.2	4.8	5.7	11.7	3.2
% ash content (air)	7.6	13.1	46.0	21.3	42.6	2.8
% ash content (dry)	8.1	14.0	48.2	22.6	48.2	2.8
% volatile matter (air)	19.6	32.4	23.8	16.5	18.0	59.9
% volatile matter (dry)	21.0	34.5	25.0	17.5	20.4	61.9
% fixed C calculation	66.0	48.3	25.4	56.5	27.7	34.1
% Total S	0.05	0.06	0.04	0.02	0.02	0.23
Ultimate analysis						
% C content	71.53	58.38	35.36	58.85	39.03	58.77
% H content	3.03	2.51	2.63	2.35	2.1	4.92
% N content	1.24	0.42	1.14	0.26	1.28	0.26
% O content	9.76	19.34	10.02	11.52	3.27	29.83
CEC (mg/kg)		6.34	12.6		3.38	7.63
pH (KCl)		3.5	6.2		6.2	4.6
pH (water)		4.69	6.7		7.3	5.9
Top Temp. °C	350	450	300 (2)	400	400	300

4.6.5 Thermodynamic analyses of two pyrolytic stoves

The temperature profiles of both the research and clay pyrolytic stoves were analyzed with thermocouples to measure heat transfer between the combustion and pyrolytic chambers. Biochar yields varied between the two stoves, with the research stove averaging 61% and the clay stove 38%. Results from the Extech datalogger are shown in Figures 4.8 and 4.9 for the small clay stove and the research stove, respectively.

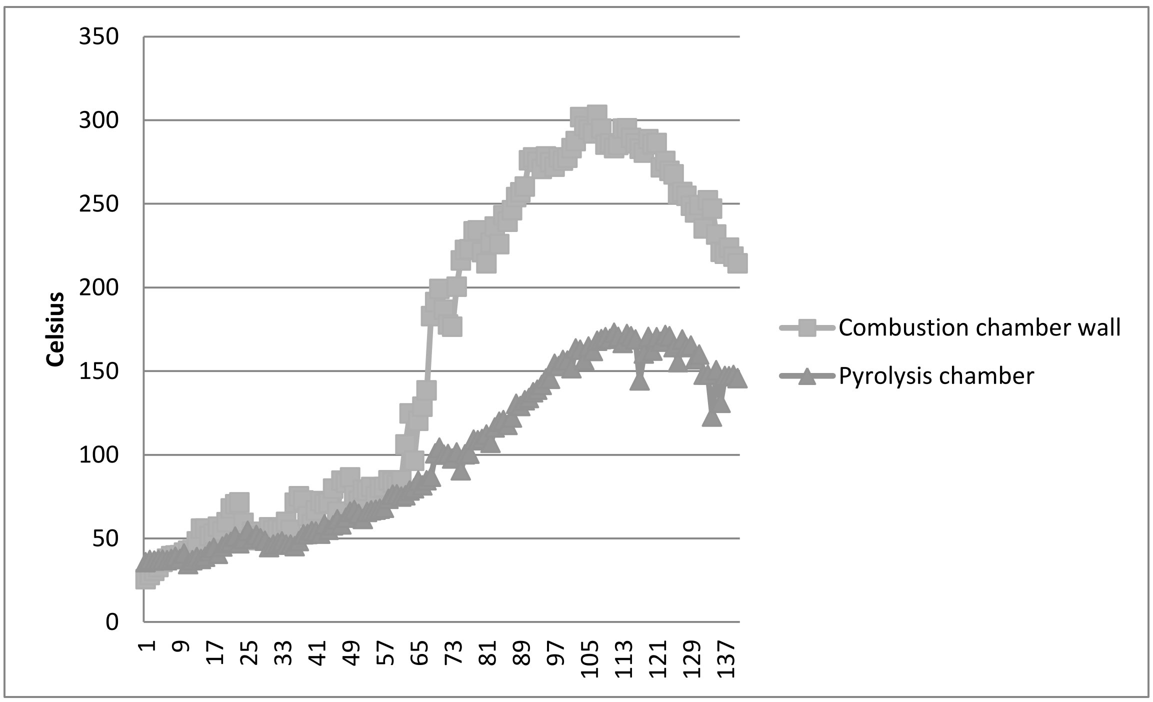


Figure 4.8 Small clay stove thermal signature

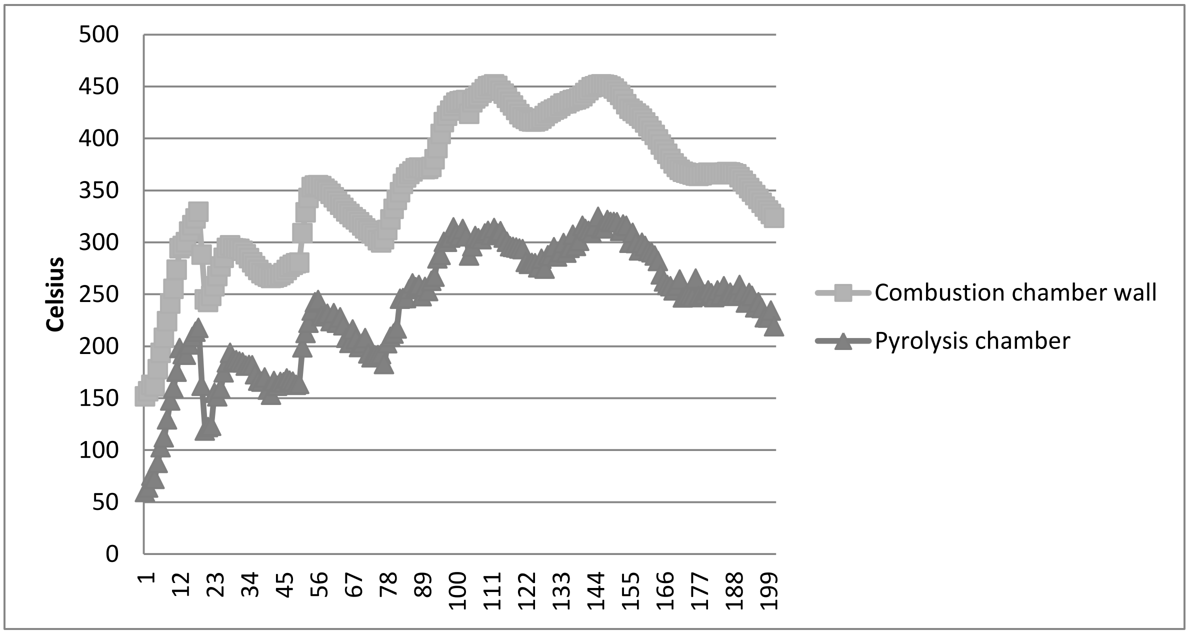


Figure 4.9 Research stove thermal signature

The research stove reached temperatures of 450°C with distinctive dips at times 27, 50 and 85 min as wood was loaded into the direct combustion chamber. Peak temperatures lasted 42 min with a total experimentation time of 200 minutes. This stove required more dry biomass (approx. 100 kg) to be loaded into the direct combustion chamber to reach required temperatures to catalyze pyrolysis of biomass in the pyrolytic chamber. The small clay stove reached 300°C for less than 20 min with 140 min of experimentation time. The small stove used less biomass (25 kg) for both the dry biomass loaded into the pyrolytic chamber and that loaded into the direct combustion chamber. Both stoves reached peak temperatures approximately 100 min after firing.

4.7 Discussion

4.7.1 Botanical composition

Though criticisms of Braun-Blanquet method exist (Goodall, 1953; Poore, 1956; Werger, 1974), it met my requirements for monitoring botanical changes. Observer bias, sampling unit size, block patterns and subjective decision making are listed among the criticisms of the Braun-Blanquet (1932) approach. Furthermore, Barbour et al. (1987) estimated that use of this method captures only 1% of plant communities, and is not a true representation of species abundance. Nonetheless, Werger (1974) promotes this method for use on large areas, since it is as reliable as other methods, cost-effective and does not require boundaries, therefore improving accuracy.

4.7.1.1 *Dichrostachys cinerea* ecology

Dichrostachys cinerea, also known as sicklebush, is a spinescent, semi-deciduous shrub found in Asia, the Caribbean and is native to Africa. Once established, trees form a thicket and create an impenetrable canopy (Richter et al., 2001). The AfroForestry Tree Database provides an elaborate description of the sicklebush (ICRAF, 2011).

Dichrostachys cinerea has been shown to rapidly establish in several environments if left unmanaged. A study in Cuba showed that if coppiced properly, *Dichrostachys cinerea* can produce 37 t biomass ha^{-1} and be grown in highly degraded soils without invading agricultural land (Carmenate, 2008). Neke et al. (2006) attributed its robustness to its ability to regrow more shoots with less die back, and be stimulated by disturbances. The study found re-sprout rates of 6%, yielding 989 kg ha^{-1} under low rainfall conditions.

Additionally, herbicides and controlled burns have proven not to prevent encroachment by this species. Post-harvest stump spraying with herbicides (ACCESS* 240 SL, Dow AgroSciences Southern Africa, Bryanston 2021, South Africa) did not prevent re-sprouting (400 ml:20 L of water with surfactant) and was costly. Controlled burns were either too hot, and provided favorable conditions for re-encroachment, or had insufficient fuel load to top-burn and kill young samplings. Of the methods tried, hand thinning for mitigating bush encroachment proved to be the best method for the harvesters and managers involved.

4.7.2 Biomass quality and biochar characterization

At low production temperatures (<350ºC), the physical geometry of woody chars remain relatively unchanged. Brewer et al. (2011) found that hardwood and softwood derived biochars exhibit different degrees of carbonization at different production temperatures resulting from the thermochemical evolution of volatile matter. Though a hardwood, *Dichrostachys cinerea* has similar lignin content to a softwood tree (*Pinus patula*), and lignin seems to play a critical role in char morphology. Sharma et al. (2004) showed that torrefaction (<200ºC) and slow pyrolysis (<350ºC) of lignin produced polycyclic aromatic hydrocarbons, with possible effects on porosity, surface area and aromaticity. In a separate study, the thermal evolution of lignin showed that liquefaction does not occur below 400ºC (Shwaiger et al., 2011). However, at higher temperatures, Sharma et al. (2001) found that pyrolysis temperature influences char morphology more than fresh feedstock quality.

Char morphology of *Dichrostachys cinerea* has not been studied in depth. As a tree adapted to a semi-arid biome, it has uniquely thick, densely fibrous cell walls composed of lignin and gum, with an intra-wall gelatinous layer consisting of cellulosic fibers that enhance water absorption (Prior and Alvin, 1986). As temperatures reach 250ºC, most cellulosic fibers depolymerize and the gelatinous layer of the cell wall thermally decomposes and shrinks. Depending on the moisture content of the fresh biomass, the decomposing layers volatilize and condense in pores, forming unknown secondary compounds. At 300ºC, lignin begins to thermally decompose and contract, rather than swell. This contraction forms pores and, as noted by Prior and Alvin (1986), produces condensed volatile matter that is resistant to heat up to 400ºC. The higher moisture content in the wood leads to faster degradation (Prior and Alvin, 1986). At these temperatures, calcium oxalate crystals react with the volatile matter. Further research should investigate if the torrefaction of higher lignin content in leguminous tree species produces biochars with higher porosity and aromaticity than those with lower lignin contents.

I hypothesize that increasing lignin content in feedstock will likely produce a char with higher fixed C and volatile matter percentages when pyrolyzed below 350°C. Since lignin produces a more C dense char at lower temperatures, I expect that volatile matter on these chars would be in higher concentrations and be less thermally labile under most pyrolysis conditions (household stoves). As pyrolysis temperatures increase beyond 600°C, volatile matter should decrease and consist of more aromatic compounds and longer-chained hydrocarbons (Spokas et al., 2011). Compounds such as dodecane, toluene and benzylaldehyde are the dominant types of longer-chained volatile C compounds produced at higher pyrolysis temperatures, but their effects on microbial communities and seed germination have shown mixed results (Spokas et al., 2011). Notwithstanding, volatile matter can be decomposed in soil and during surface oxidation, also known as activation. Activation is a critical process used to expedite the increase in CEC (Glaser et al., 2002; Keech et al., 2004; Liang et al., 2006; Deluca et al., 2009) and therefore improve biochar performance in agricultural applications.

It has now been shown repeatedly that fresh biochar rarely improves soil fertility or increases plant growth. Fresh chars lack adsorption capacity, which develops over time as the char is "weathered". Aging of the biochar through surface oxidation increases both anion exchange capacity (AEC) and CEC (Cheng et al., 2006). Natural surface oxidation of biochar occurs by multiple factors including, microbial activity and abiotic processes (chemical and physical weathering) over time (Cheng et al., 2006). Artificially aging biochar and/or naturally increasing surface oxidation over time can improve biochar quality and its beneficial functions. However, alkaline biochars and those with high ash contents can have a liming effect, which has been shown to reduce soil acidity and improve plant growth in acidic, highly weathered oxisols, even without aging. As I discovered, activating a char produced at low temperatures is difficult with local resources, nevertheless, biochar will oxidize slowly once added to soil.

4.8 Conclusion

4.8.1 Key findings

Bush-derived biochars can be a practical method of reversing soil degradation in northern South Africa. Bush encroachment poses a serious threat to savannahs by lowering their carrying capacity to sustain wild game, decreasing net primary productivity, altering biological balances in favor of woody species, reducing soil moisture, and preventing access by humans and game alike. Methods to mitigate this problem have varied, but in this study, I found that hand-thinning through participatory involvement of local villagers can be an effective way to thin savannahs, while at the same time providing fuel-wood for harvesters. Furthermore, the harvested fuel-wood could be pyrolyzed in locally produced stoves to provide fuel for cooking and produce biochars for household agricultural plots. Additionally, pyrolytic cook stoves could potentially improve indoor air quality and increase biomass fuel use efficiency; therefore, decreasing the demand for fuel-wood, easing pressure on forest systems. Coppicing of encroaching trees can also be a method of attenuating fuel-wood demand and providing space for herbaceous cover to re-establish itself. In this study, herbaceous cover re-established quickly and provided sufficient fuel loads for future controlled veld fires that help prevent re-encroachment.

A holistic, systems approach can provide synergies between the rural poor, large agricultural enterprises, and savannah health. Altogether, bush encroachment can provide an opportunity for many and no longer be a threat to fragile savannah ecosystems. The maintenance of natural capital requires action from all actors who derive their sustenance from it; otherwise accelerated degradation will deplete natural resources and marginalize subsistence farmers even further. Use of integrated biochar systems in sub-Saharan savannahs can be a method to combat global climate change, reverse soil degradation, provide fuel-wood for villagers, and be a vehicle to transfer technology and knowledge to displaced farmers and provide market access.

An archeological study of the Lowveld savannahs investigated the link between tree harvester preference and charcoal properties (Shackleton and Prins 1993). The results indicated that *Dichrostachys cinerea* is historically a high yielding char and is a preferred fuel-wood because of its highly dense, low shrub-like canopy. My analysis of *Dichrostachys cinerea* showed that this feedstock does produce dense chars with high contents of fixed C and volatile matter, when pyrolyzed in the household, clay pyrolytic cook stove. During slow pyrolysis, the fibrous plant tissue thermally decomposes to produce high aromaticity and high yielding char (>50%) while less labile lignaceous material inhibited the de-polymerization of cell walls. Harvesting encroaching bush species is an opportunity to restore savannah ecology and can benefit local villagers.

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CHAPTER 5: CONCLUSION

5.1 Future implications

The harvesting of encroached savannahs is not without precedent. The Works for Water Program (Turpie et al., 2008) and Community Based Natural Resource Management (Fabricius et al., 2004) are projects that have been successful in linking local people with government and large swaths of privately owned land for fuel-wood harvesting. However, control in thinning operations must be done to prevent over-harvesting, which in turn can lead to erosion, biome shifts, and criticisms of biomass harvesting such as those put forward by Biofuelswatch in their criticism of biochar science and policy (Biofuelswatch, 2011). Careful consideration has been paid to the use of non-competing sources of fuel-wood, with special attention paid to enhancing natural capital. Integrated biochar systems can provide beneficial outcomes, if managed properly.

Existing charcoal markets have led to over-harvesting of “the commons” and illegal harvesting of both beneficial and encroaching tree species. If improperly managed, biochar marketing could lead to further degradation and promote illegal harvesting. Regulatory bodies to manage biochar production in South Africa do not exist, nor have international organizations provided suitable frameworks for projects like AfroChar™. The lack of both can threaten the adoptability of biochar as a soil amelioration and climate mitigation strategy and the use of pyrolytic stoves for increasing fuel wood use efficiency, and therefore would hinder the use of integrated biochar systems for poverty alleviation. A refined pedagogy must be available and feasible to small farmers to effectively manage the environment for fuel and biochar production.

Future studies should include testing the benefits of micro-dosing biochar into planting holes to avoid mass thermal conversions of fresh biomass or the use of blanket applications. Current research (Lehmann and Rondon, 2006; Major, 2009) has shown that 12 – 30 t biochar ha^{-1} can increase productivity and improve soil health. However, such large applications are not feasible for small-holder farmers or environmentally friendly since thermal conversion rates of fresh feedstock average from 30 – 60%, depending on the stove technology. Small stoves can yield about a ton of char per year which can be used successfully in pit farming and accrue biochar over a temporal scale suitable to sustain ecosystem health. Pit or Zaï farming (Itani, 1998; Roose et al., 1999; Reij and Waters-Bayer, 2001) is a traditional dryland farming system where pits (permanent holes) are dug to capture sediment and litter fall, and later form islands of fertility in arid soils. Pits with biochar additions may improve soil fertility by preventing the leaching of nutrients and helping to accrue biomass in concentrated areas where crops are planted, thereby, maximizing the benefit of biochar inputs in small-holder farming systems.

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Appendix A

Biochar stove design