IMPACT OF A RAINFALL GRADIENT ON CARBON STORAGE IN THE DRY WOODLAND ECOSYSTEM OF KAVANGO AND ZAMBEZI REGIONS OF NAMIBIA

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Thesis submitted in partial fulfilment of the requirements for the degree of Master of Spatial Science at the Namibia University of Science and Technology

NAMIBIA UNIVERSITY OF SCIENCE AND TECHNOLOGY

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APRIL 2018

Declaration

I, *Amber Jeanne Nott*, hereby declare that the work contained in the thesis entitled: *Impact of a rainfall gradient on carbon storage in the North-eastern Namibian dry woodland ecosystem* is my own original work and that I have not previously in its entirety or in part submitted it at any university or higher education institution for the award of a degree.

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List of Acronyms

AIC	Akaike Information Criterion
ANOVA	Analysis of Variance
CBD	Convention of Biological Diversity
CF	Community Forest
CITES	Convention for international Trade in Endangered Species of Wild Fauna and Flora
cm	Centimetre
CO_2	Carbon dioxide
CoP	Convention of Parties
DBH	Diameter at breast height
DoF	Directorate of Forestry (Namibia)
FAO	Food and Agriculture Organization
GLM	Generalised linear model
GRN	Government of the Republic of Namibia
GPR	Ground Penetrating Radar
HSD	Honest Significant Difference
IRDNC	Integrated Rural Development and Nature Conservation
IUCN	The World Conservation Union
KAZA	Kavango-Zambezi Transfrontier Area
KM	Katima Mulilo
LTAR	Long-term Annual Rainfall
m	meter
MAWF	Ministry of Agriculture, Water and Forestry (Namibia)
MET	Ministry of Environment and Tourism (Namibia)
ND	Non-destructive
NPC	National Planning Commission
NUST	Namibia University of Science and Technology
REDD+	Reduction in Emissions from Deforestation and Forest Degradation in Developing Countries
SADC	Southern African Development Community
SASSCAL	Southern African Science Service Centre for Climate Change and Adapted Land-Use
SD	Standard deviation
TC	Tonnes of CO_2
UNAM	University of Namibia
UNFCCC	United Nations Framework Convention on Climate Change

Acknowledgements

Appreciation goes to the Southern African Scientific Service Centre for Climate Change and Adaptive Land Use (SASSCAL) Task ID 033 for funding the study and my bursary at Namibia University of Science and Technology.

I would like to acknowledge the following people and institutions, in no particular order, of importance for their various contributions to the successful completion of this study:

- To my supervisor, Dr. Nichola Knox (Namibia University of Science and Technology) and my co-supervisor, Dr. Vera De Cauwer (Namibia University of Science and Technology), for all of the support throughout my studies.
- The staff members at Namibia University of Science and Technology who assisted with my additional laboratory work.
- My field assistants, who greatly assisted me with my data collection.
- Directorate of Forestry colleagues, with assistance with the permits and also their knowledge of the area.
- To my parents, Steve and Terry Fisher, whose love and hope got me through all of my tough times throughout the process. Thank you for the instilling the love of nature in me.
- To my husband, Jason Nott, who I could not have done this without.

Dedication

To my greatest support throughout this whole process, I dedicate my thesis to my husband, Jason Nott.

Abstract

Namibia is currently a signatory on the United Nations Framework Convention on Climate Change (UNFCCC) as a non-Annex I party. As a non-Annex I party, Namibia is required to 'provide information on greenhouse gas inventories', but they currently lack sufficient baseline data. The study aims to answer whether increased rainfall increases the amount of carbon stored above and below ground for two important timber species (*Burkea africana* and *Pterocarpus angolensis*) found along the natural rainfall gradient in North-eastern Namibia. From this aim, three research objectives were set. The first is to compare whether rainfall results in statistically different non-destructive measurements in the tree species investigated. The second is to develop and compare different allometric models that link non-destructive measurements of trees to above and below ground carbon values, to determine which produces the highest accuracy (about 30% uncertainty level). The third is to determine whether rainfall influences woody biomass for either species.

Four study sites along this rainfall gradient (Long term average rainfall-LTAR) were chosen (Nkurenkuru where the LTAR amount falls between 550-600 mm, Mashare where the LTAR falls between 500-550 mm, Divundu where the LTAR amounts falls between 550-600 mm and Katima Mulilo where the LTAR is greater than 600 mm). Non-destructive sampling was conducted at all sites, at these sites multiple tree parameters (height, dbh, etc.) were measured in 5 dbh classes from 5cm - >45cm. In addition, at one site, destructive sampling was conducted where the above and below ground woody components were weighed in the field. Between 3 -5 sample discs and one root sample were taken from each destructively harvested tree and dried in the laboratory. From this site, allometric biomass models were derived and extrapolated using the measured non-destructive parameters to the remaining 3 sites.

For *B. africana*, all tree parameters differ significantly across the sites and higher rainfall causes higher woody biomass in this species. For *P. angolensis,* all tree parameters except bark thickness differ significantly across the sites, but an increase in rainfall does not cause a higher woody biomass in this species. For both species, allometric models were developed to model the above and below ground carbon levels, but the models which included total biomass did not meet the 30% uncertainty level. When looking at only above ground biomass, models were fitted for both of the species which met the 30% uncertainty level. The mean biomass and carbon values followed the rainfall gradient as expected with Mashare having the lowest values with the lowest LTAR and Katima Mulilo having the highest values with the highest LTAR.

Keywords: *Pterocarpus angolensis (kiaat)*, *Burkea africana*, carbon storage, rainfall gradient

Chapter 1: General Introduction

1.1 Background

Namibia is currently a signatory on the United Nations Framework Convention on Climate Change (UNFCCC) as a non-Annex I party (Government of the Republic of Namibia 2015). By being a signatory, it is the responsibility of the country to submit national reports on the implementation of "The Convention" to the Conference of the Parties (COP). As a non-Annex I party, Namibia is required to 'provide information on greenhouse gas inventories, measures to mitigate and to facilitate adequate adaptation to climate change' in the form of a national communication. "Update Reports" must be submitted biennially, while the national communications must be submitted every four years. Namibia last submitted their report in December 2015. As a part of this report, Namibia must report on the greenhouse gas emissions as well as carbon storage.

Currently, Namibia is not involved in the United Nation's Programme for Reduction in Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+). By assessing the carbon storage capabilities in the largest woodlands of Namibia, there will be an opportunity for Namibia to become involved with this programme while conserving the woodlands. The REDD+ programme aims to enhance the livelihoods of people by facilitating the development of voluntary markets and international agreements to credit communities for afforestation and conservation of carbon activities (Eggleston 2006). Namibia is lacking most of the baseline data on carbon storage to enable them to benefit from the carbon trading mechanisms under negotiation considered by the UNFCCC.

By beginning to monitor deforestation and the estimation of carbon storage in the Namibian woodlands in Kavango and Zambezi regions, it would allow forestry members to make informed decisions about the evaluation of land clearing for carbon credits. It will also allow more informed reporting to the UNFCCC. Therefore, reliable information is needed to quantify the conversion of woodland to open rangeland or to agricultural lands and subsequently estimate the future availability of woodland resources. In addition, deforestation has significant influence on the carbon stored in the native vegetation and soils (Covey and Orefice 2009).

According to a Food and Agricultural Organisation of the United Nations study (2010), about 730 km² of forest cover is declining annually in Namibia. This estimated rate has been shown to be inaccurate (De Cauwer 2015b), as the only inventory done is over 10 years old and these numbers were based on a simple time series extrapolation. The actual rate of loss is not being monitored for sustainable use of the woodlands, and thus the exact statistics of the land cover change is unknown. While some of this loss is brought about by land clearing for agriculture (Mendelsohn and el Obeid 2003), a large proportion of forest cover is lost as woodland density declines (Brown 1997). In the past few years, deforestation has been seen as a reduction in carbon storage capacity of the woodlands (Covey and Orefice 2009). This refers to the substantial amounts of carbon that are stored in the above and below ground parts of trees (Mugasha *et al.* 2013), which are then released into the atmosphere, or lost from the ecosystem, when deforestation occurs.

Along with deforestation, climate change is greatly affecting the rural populations in Namibia. Changes in rainfall patterns and temperature have caused changing crop yields and therefore have caused essential livelihood changes for these rural populations (Mendelsohn and el Obeid 2003). This has, in turn, put pressure on the Namibian government to provide support to the rural populations for food and income security. With the impacts of climate change currently being felt in this region, carbon storage is not only an environmental concern with regards to biodiversity and ecosystem health but is also a potential business opportunity for Namibia.

Carbon is naturally stored in the biomass of woodlands, both above and below ground as well as in the soil they are located in (Forest and Wood Products Australia 2014). Carbon dioxide is naturally converted into organic matter by photosynthesis, whereby the flux carbon is converted to a stable form and stored in the above and below ground biomass for a period of time (Houghton and Hackler 2006). The amount of carbon stored in the biomass of a plant changes per species, moisture content and also the soil type, but most of the carbon which is naturally converted is kept in the biomass of the plant (Whittaker *et al.* 1974). The amount of carbon that is stored in the woodlands directly relates to the stability of the ecosystem (which takes into account temperature, light, soil and moisture conditions (Whittaker *et al.* 1974)) and is an important variable in climate models. Ultimately, this carbon is returned to the atmosphere through respiration, decomposition or a disturbance (such as deforestation or fire) (Mugasha *et al.* 2013). In most situations, when deforestation occurs, the carbon that has been stored in the biomass of that woodland is then released or lost to this environment. These changes in the carbon state provide great uncertainty to understanding carbon models, in turn uncertainty as to the impacts on the climate (Mugasha *et al.* 2013).

A change in the amount of woodland biomass is directly related to the amount of carbon stored, but some species are better at storing carbon for longer period of times than others (Whittaker *et al.* 1974). A woodland's ability to store carbon changes, as average tree size and woodland structure changes. In most cases, woodlands in early stages of development use most of their carbon for shoot and root growth (Hunziker 2011). This then changes to stem growth, to bole wood and finally to woody branch growth as the trees mature. As trees mature, they tend to take in less and less carbon due to physical limitations, such as water stress (Whittaker *et al.* 1974). Over time, carbon is constantly lost due to respiration and the aging of leaves, roots, branches and bark. However, some of the carbon stored in this material remains on site as coarse woody debris, leaf, and branch litter, and soil organic matter (Covey and Orefice 2009) and is not released into the atmosphere.

For the species found in the woodlands of Kavango and Zambezi regions, only one study by Moses (2013) in Kavango East has been done on the carbon storage on one species, but no study has been done on the differences between the species and their above and below ground carbon storage capabilities. The main hardwood canopy species found, in the Namibian dry woodlands, are *Pterocarpus angolensis, Burkea africana, Baikiaea plurijuga* and *Guibourtia coleosperma* (De Cauwer 2015a). By collecting data about some of these key species and their carbon storage capabilities, information can be relayed to the forestry authorities to make informed decisions about which areas they decide to de-bush or convert into agricultural land.

Currently, Namibia's woodlands consist of over 4,000 species of plants, but only 10% of these are woody species (Mendelsohn and el Obeid 2003). Out of these woody species (the main hardwood canopy species found), this study will look at *B. africana* and *P. angolensis*. These two species were chosen since they are of high international and local importance. Namibia's woodlands, and specifically the timber resources are very limited in their distribution (Mendelsohn and el Obeid 2003) and many of the high valued species are selectively used by the local populations. These hardwood trees support hundreds of thousands of people in Namibia, especially in the Kavango and Zambezi regions where many people directly sustain livelihoods by extracting both *B. africana* and *P. angolensis* timber for wood carving, furniture, construction and occasionally fuelwood (Mendelsohn and el Obeid 2003). The Zambezi and Kavango regions together cover an area of 63,527 km^2 (Mendelsohn 1997), with 44.4% woodland cover in Zambezi and 88.6% cover in the Kavango Regions (De Cauwer 2015b). These areas also support a large percentage of the population (Mendelsohn 2005). 16% of the Namibian population live in these two regions having a population density of 5.35 per km^2 which is double the national population density of 2.6 per km^2 (National Planning Commission, 2013).

1.2 Problem Statement

Currently, Namibia is not involved in the REDD+ programme. By assessing the carbon storage capabilities in the woodlands of northeast Namibia, there will be an opportunity for Namibia to become involved with this programme while conserving their woodlands. This programme aims to enhance livelihoods and local economies by facilitating the development of voluntary markets and international agreements to credit communities for afforestation and conservation of carbon activities (Eggleston *et al.* 2006). The problem at this time is that Namibia is lacking most of the baseline data, which will enable them to benefit from the carbon trading mechanisms under the negotiations being considered by the UNFCCC. Little is also known about the woodlands of Namibia, especially their sustainable harvesting rates and wood production capacities (Strohbach 2013). Therefore, reliable information is needed to quantify the conversion of woodland to open rangeland or to agricultural lands and subsequently estimate the changes to carbon stocks and by association also outline the future availability of woodland resources.

1.3 Research Objectives and Questions

The objective of this study is to create a means to derive a baseline of carbon storage data, for important timber species growing in the woodlands of northeast Namibia (Kavango West, Kavango East and Zambezi regions). Across these woodlands in Namibia, there is a rainfall gradient increasing from south to north and from west to east. The study aims to specifically answer whether an increase in rainfall increases the amount of carbon stored above and below ground for two of the high valued woody species (*B. africana* and *P. angolensis*) along the west to east gradient.

Derived from this aim, the following research objectives were established:

1.) Compare whether rainfall results in statistically different non-destructive measurements in the tree species investigated.

H_o: Measured tree parameters (for both species or irrespective of species) do not differ statistically across the rainfall gradient.

H_a: Measured tree parameters (for both species or irrespective of species) differ statistically across the rainfall gradient.

2.) (a) Develop allometric models that link non-destructive tree measurements to above and below ground carbon values in Namibian woodlands.

(b) Assess the developed allometric models (validation and parsimony) to determine which can produce an accuracy below 30% uncertainty level at only tree level (which is the accepted percentage by REDD+ reporting countries (USAID 2013)).

H_o: Non-destructive measurements of trees cannot credibly (above 30% uncertainty level) be used to model above and below ground carbon values.

H_a: Non-destructive measurements of trees can credibly (below 30% uncertainty level) be used to model above and below ground carbon values.

3.) Determine whether rainfall influences woody biomass for either *P. angolensis* or *B. africana.*

H_o: Increases in rainfall do not change the amount of woody biomass for either species.

H_a: Increases in rainfall create a significant increase in woody biomass for either species.

1.4 Literature Review

1.4.1 Woodlands in Namibia and their value

Namibia's vegetation types are divided into savannahs (64%), deserts (16%) and woodlands (20%) as outlined by Mendelsohn and el Obeid (2005). Trees in the Namibian woodlands are sparsely distributed; small in size, and grow slowly. Woodland growth and structure are greatly affected by widespread and frequent bush fires (Mendelsohn and el Obeid 2005). The Namibian woodland area inclusive of savannahs and woodlands also decreased between 1990 and 2005 (Food and Agriculture Organisation of the United Nations 2010) as result of urban settlements and woodland clearing to make way for agricultural fields. Although, in general, the Namibian woodlands are considered unsuitable for industrial timber or pulp, existing timber resources support local livelihoods (Mendelsohn and el Obeid 2005).

When considering the management of woodland resources in Namibia, it is essential to consider the type and extent of these resources, which is widely unknown (Strohbach 2013). The woodlands of Namibia occur mainly in the deep Kalahari Sands (el Obeid and Mendelsohn 2001), in the north-central and north-eastern parts of the country (Mendelsohn and el Obeid 2005). Namibia's woodlands can rather be described as dry, semi-open to open woodlands. The most important factors affecting the development of woodlands in Namibia are the soils, the availability of moisture and the occurrence of fire (Mendelsohn and el Obeid 2005). The region with the highest wood volume is Kavango (which is now two regions – Kavango West and Kavango East) which has 34% of Namibia's standing stock of wood (Pröpper 2009).

In the Kalahari Sands Woodlands, the dominant tree species belong, as is the case with the dry Miombo Woodlands, to the subfamily Caesalpinioideae (Ministry of Agriculture, Water and Forestry 2011). The Kalahari Sands Woodlands vegetation type (or sometimes referred to as North Eastern Kalahari Woodlands by Mendelsohn and el Obeid 2005) is also found in Angola, Northern Botswana, Zambia and Zimbabwe. The Caesalpinoid species typical of these ecosystems are *Baikiaea plurijuga*, *Burkea africana*, *Guibourtia coleosperma* and *Colophospermum mopane* (Mendelsohn and Robert 1997). Species such as *P. angolensis*, *Sclerocarya birrea*, *Terminalia sericea* and *Schinziophyton rautanenii* are also important (Ministry of Agriculture, Water and Forestry 2011). In Namibia, the woodlands are dominated by six tree species which represent 84% of the basal area (De Cauwer *et al.* 2016).

The vegetation of the central and southern Southern African Development Community (SADC) countries have several hardwood species that are heavily exploited for commercial use within these countries but are also exported (Mendelsohn and el Obeid 2005). One of the principal hardwoods that are removed in large quantities is *P. angolensis,* and the sustainability of these logging practices has been questioned (Moses 2013, Pröpper 2009). Historically, the timber species that have been exploited commercially from the Kalahari Sands Woodlands have been restricted to *P. angolensis* which also occurs in the Miombo Woodlands, and *B. plurijuga* which is confined to the Kalahari Sands Woodlands (Ministry of Agriculture, Water and Forestry 2011).

Kojwang (2000) estimated the economic value of forest resources in Namibia at NAD 1.05 billion annually with firewood and charcoal having the largest value of all the categories considered. Kojwang (2000) stated that commercial logging of *P. angolensis* and *B. africana* contributed NAD 2.4 million annually. Namibia is a net importer of industrial wood and wood products and Kojwang (2000) predicted that this would not change. Due to the timber resources in Namibia being spread over large areas with difficult access, all timber used to build and furnish modern houses is imported, mostly from South Africa and is either pine or processed chipboard, both of which are cheaper than indigenous timber (Mendelsohn and el Obeid 2005).

In 2001, the forest revenue collected by DoF was NAD 420 000 compared to the budget of the Directorate which was NAD 14 849 000 (Chakanga and Kojwang 2001). The bulk of the revenue was generated in Kavango region from the sale of timber. The operational budget for DoF for the 2013/2014 financial year was NAD 114 985 137 and the forest revenue collected from sale of forest products was NAD 521 734 (Ministry of Environment and Tourism 2014). The completion of the forest resource inventory enabled a set of preliminary forest resource accounts to be developed for the whole country (Barnes *et al*. 2005, Barnes *et al*. 2010). The total woody volume for Namibia in 2004 was estimated to be 257 million m^3 with a value of current forest use of NAD 1.2 billion and a contribution of 3% to the GDP. Namibia's standing forest assets were estimated to have a value of NAD 19 billion (Barnes *et al.* 2005, Barnes *et al.* 2010).

The study undertaken in Kavango East region by Moses (2013) found that *P. angolensis* planks were identified as the most important wood product. The average plank was found to have a length of 257.8 cm, width of 23.8 cm and thickness of 3.7 cm with a volume of 0.023 m^3. The average volume of the 40 *P. angolensis* merchantable logs harvested by Moses (2013) was 0.4 m^3 and yielded 11 planks per tree. Only 23% of the above-ground tree was extracted in the form of merchantable logs. Moses (2013) also showed that harvesting of these trees provided a greater economic benefit to the local communities than carbon accounting could offer.

1.4.2 *Burkea africana*

B. africana is a deciduous tree with a rounded to flattened crown and is described as a medium sized tree species that ranges in height from 8-10 m (Figure 1). Although Mannheimer and Curtis (2009) stated that the tree can grow up to 20 m high in Namibia and other areas of its distribution outside of Namibia and De Cauwer (pers comm) confirmed that within the Kavango region they have measured individual trees as high as 20 m. The rooting depth is between 4 – 5 m. In Namibia, it is confined to the Kalahari Sands of the central-north and north-eastern areas of Namibia (Figure 2), as it occurs in savannahs and woodlands with dry and sandy soils. The trees have a grey to dark grey rough bark (Mannheimer and Curtis 2009). Their distinguishing characteristic is velvety reddish brown growth point on the branches, which distinguishes it from the species *Erythrophleum africanum.* The species is noted to produce heavy, tough wood which has variable colours but is described as being easily susceptible to wood borers and 85% of all trees are believed to be hollow and sand-filled (Mannheimer and Curtis 2009).

Figure 1: An example of a Burkea africana tree in Divundu (Kavango West Region)

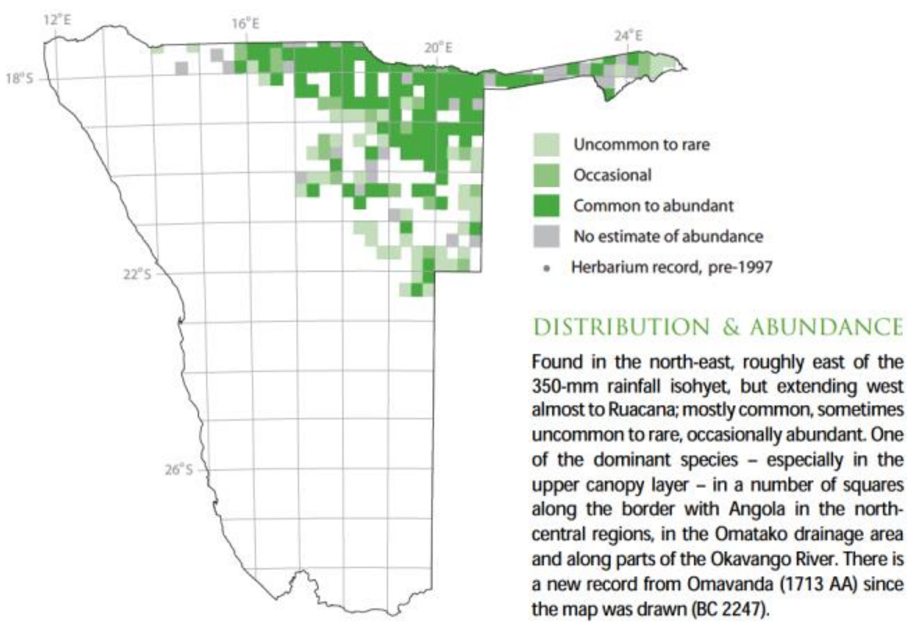

Figure 2: Distribution and estimates of abundance of Burkea africana in Namibia (From Mannheimer and Curtis *2009)*

When damaged, the tree exudes a yellowish red resin which is edible and used locally. The wood is very dense, hard and dries slowly. It has a density between 735–1020 kg/m³ at 12% moisture content (Kojwang 2011). It can be easily sawn or processed, and is commonly harvested for use as poles, firewood and for the production of charcoal. Due to it being a shorter timber tree in Namibia, its uses have not extended to furniture and flooring. Currently, *B. africana* provides the largest contribution to basal area in the north eastern Namibian Dry Savannah Woodlands (De Cauwer *et al.* 2016). The Namibian permit data (TRAFFIC 2015) indicates that *B. africana* is most commonly harvested for use as firewood and poles. *B. africana* is used locally in Namibia for poles for construction and fencing but little evidence was found of it being made into planks and exported as timber.

Among its diverse uses, the species' bark is used in enhancing alcoholic brews, as a fish poison when crushed and the tree produces an edible resin (Mannheimer and Curtis 2009). *B. africana* is also described as having an adaptation whereby it is able to resprout from its growing points in response to disturbance such as fire or herbivory (Kabajani 2016). The species has been found to be significantly influenced by herbaceous cover and tree cover. Kabajani (2016) stated that variations in basal area between sites influenced the seed availability of the species and ultimately influenced recruitment of the species. It was noted by Kabajani (2016) to be one of the tree species that livestock do not target for browsing in the Kavango region. *B. africana* is able to tolerate high fire frequencies (Burke 2006), as well as being best suited to harsh climatic conditions and is drought resistant. It is able to resprout after fire, frost and herbivory (Burke 2006).

1.4.3 *Pterocarpus angolensis*

P. angolensis is a medium to large sized deciduous tree that grows up to 30 m tall (Mannheimer and Curtis 2009), although in Namibia it generally reaches a height of between 17-20 m (Figure 3). The rooting depth is between 7 – 10 m. The distinctive fruit is a spherical pod, 70 - 120 mm in diameter. The central portion is raised with stiff bristly hairs encircled by a papery wing which is up to 50 mm broad (Mannheimer and Curtis 2009). It has a long period of leaflessness often from May to October (De Cauwer *et al*. 2014). The brilliant, dramatically red sap that it exudes gives it the common name of "*bloodwood*". Within the study area it is commonly referred to as "mukwa".

Figure 3: An example of a Pterocarpus angolensis tree in Katima Mulilo (Zambezi Region)

The distribution of *P. angolensis* within Namibia is in the north-eastern sandy plains and dunes (Mendelsohn and el Obeid 2005) east of the 400 to 450 mm rainfall isohyet (Figure 4). This includes the following regions: Zambezi, East Kavango, West Kavango, Ohangwena and parts of Oshikoto and Otjozondjupa regions where most of the rainfall occurs in January and February (Mendelsohn and el Obeid 2005). Within this range, it is locally abundant and one of the dominant species in the regions (Mannheimer and Curtis 2009). This species is light-demanding (Mannheimer and Curtis 2009). *P. angolensis* trees tolerate a wide range of environmental conditions but generally they are limited to deep sandy soils (Mendelsohn and el Obeid 2005) in areas where rainfall exceeds 400mm/year and where there is a dry season contrasting with a wet season (Mendelsohn and el Obeid 2005).

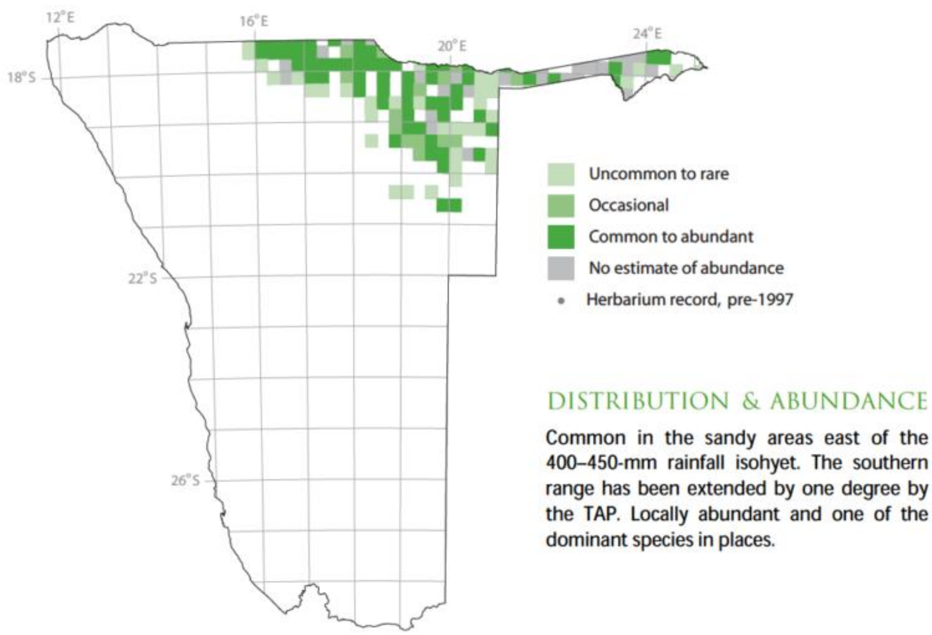

Figure 4: Distribution and estimates of abundance of Pterocarpus angolensis in Namibia (From Mannheimer and Curtis 2009)

Populations of *P. angolensis* are characterized by having more old trees and relatively fewer younger trees (Mendelsohn and el Obeid 2005). Although a large number of seeds are produced, only 2% germinate under natural conditions (Moses 2013). Typically, *P. angolensis* trees remain within the suffrutex stage for about 10 years – the seedlings grow but die back each dry season – and only after ten years do they develop into trees in the zero to five cm diameter class (Pröpper *et al*. 2015).

The woodlands where *P. angolensis* trees are found are characterized by disturbances, especially fire (Mendelsohn and el Obeid 2005) and shifting cultivation (De Cauwer *et al*. 2014). This species is generally thought to be able to withstand some fire (Moses 2013) since it dies back to the woody rootstock and then coppices during the next season. Fire does assist with breaking open the seed pods to release the seeds and total protection from fire results in a decrease in recruitment (Mannheimer and Curtis 2009). Pröpper *et al.* (2015) found that at their study sites in Kavango East and West regions, the main cause for tree damage was fire. Extreme cold events can have an effect on the flowering of *P. angolensis* (Mannheimer and Curtis 2009). The average trunk (bole) volume of *P. angolensis* in the Namibian Kalahari Sands Woodlands is 0.19 m^3 and its contribution to the total wood volume is 14% (Pröpper *et al.* 2015).

De Cauwer *et al*. (2014) developed models to estimate the current distribution of this species and its environmental requirements in order to obtain a potential distribution. Their results showed more details for the environmental requirements for *P. angolensis* than those previously described in the literature. They found that the distribution of the species is mainly influenced by the amount of summer rainfall, by the minimum temperature in winter and by temperature seasonality. De Cauwer *et al.* (2014) determined that *P. angolensis* is mainly found in areas with an annual fire frequency below 45%. This study concluded that climate change can decrease the species range considerably and threaten the species existence in Namibia and Botswana (predicted decrease in species distribution area of up to 50%) while potentially increasing it in Zambia. De Cauwer *et al.* (2016) also considered the environmental drivers of change in the transition zones of woodlands in Namibia. This study concluded that while *P. angolensis* communities were better able to withstand high fire frequency than other communities, they show a higher vulnerability to climate change.

P. angolensis is one of the most important timber species in southern Africa because of its attractive and stable hardwood (Pröpper *et al.* 2015). The wood from this species varies greatly in colour and weight. The sapwood is yellow while the heartwood ranges from light brown to dark reddish-brown. The sapwood is subject to borer beetles (Mannheimer and Curtis 2009). Its density is 400–700 kg/m³ at 12% moisture content (Moses 2013). The brown heartwood is resistant to borers and termites, is durable and polishes well, making it suitable for the production of furniture. The wood saws and planes easily, glues and screws well and shrinks very little when drying. When cut, it exudes a red, sticky sap which contains 77% tannin and is an effective dye (Mannheimer and Curtis 2009).

1.4.4 Measuring carbon storage in trees and the effects of rainfall

Since woodlands are sinks which naturally absorb carbon dioxide and carbon dioxide is one of the greenhouse gases from the atmosphere causing global warming (Ryan *et al. 2011*), it is imperative to understand how this gas is stored. The gas is stored in the biomass and soil; therefore, woodlands help to mitigate the challenges of climate change (Ribeiro *et al.* 2011). The discussion about carbon storage and sequestration in woodlands, is increasing to looking at options in order to increase carbon storage and sequestration through forest management.

Carbon dioxide is sequestered in the process of photosynthesis and stored in the form of biomass of the trees. Limited and fragmented information is available on growth, carbon storage, and sequestration in the Namibian woodlands, especially with a focus on the high valued species. Furthermore, there is inadequate information about the effect of the REDD+ climate change mitigation practices on the biomass of these woodlands, carbon storage and sequestration.

The biomass stock is an immediate measure for the quantity of carbon that will be emitted to the atmosphere when the corresponding area is converted to another land use through burning and decay (Ribeiro *et al.* 2011). Biomass itself cannot directly be measured or observed in the field, so when individual tree biomass is to be estimated allometric models are among the standard tools for biomass prediction. An allometric model is an empirical relationship between biomass and easily measured variables, such as tree diameter at breast height that can be established by means of a regression analysis (Ryan *et al.* 2011). Such models are valid and should only be applied to the species or species group for which they were derived (Ribeiro *et al.* 2011) Many of these models do not incorporate enough measurements and therefore suffer. There are no such models which exist for the specific trees in this study despite general equations being developed for miombo woodlands in Southern Africa (Ryan *et al.* 2011). Picard *et al.* (2012) developed a methodology for deriving species specific allometric models in different land cover types, and these methods were used to create the allometric equations since no such models exist for the target species of this study.

Multiple studies in South Africa and Panama have looked at the effects of rainfall on tree growth and in turn carbon storage capabilities. This has not yet been done in Namibia. In North-eastern Namibia, a natural rainfall gradient occurs from west to east (Ministry of Agriculture, Water and Rural Development 1999), and both *B. africana* and *P. angolensis* occur along its extent. Along the natural rainfall gradient in Panama, species reacted very differently to the amount of rainfall. The rainfall not only increased tree growth, but caused higher tree mortality during drought years (Condit *et al.* 2004). Shackleton *et al.* (2005) showed that there was a gradient of increasing woody density and height of the canopy as rainfall increased in the lowveld in South Africa. Their research also showed that the above ground carbon storage was higher as the rainfall increased (Shackleton *et al.* 2005). The output of the research by Shackleton *et al.* (2005) which demonstrated that rainfall amounts increase the carbon storage abilities of trees was used as the foundation of the objectives to understand how rainfall affects the above and below ground carbon storage in the Namibian woodlands. In Namibia, there has been very limited research done on above and below ground carbon storage. Moses (2013) studied *P. angolensis* (above ground only) specifically in the Kavango East region and his methodology was reviewed to investigate the practical implications of extending these methods into other regions and species.

Through the literature search, two additional papers Ribeiro *et al.* (2011) and Ryan *et al.* (2011) were found to be the most useful in developing the research design. Both of these articles focussed on above and below ground carbon estimations. For this study, the above ground biomass specifically refers to all living biomass that is above the soil (including stems, stumps, branches, bark, seeds and foliage). The below ground biomass includes all living biomass of coarse living roots (thicker than 2 millimetres in diameter). The total organic carbon (or soil organic carbon/below ground carbon) includes all the organic material in the soil to a depth of 1 meter, but excluding the coarse roots of the above ground pools (USAID 2013).

1.5 Thesis outline

This thesis consists of five chapters. Chapter 1 presents the introduction in which the problem statement, main aim and objectives, specific questions, scope and a literature review are provided. Chapter 2 presents the methodology and methods of the study. Chapter 3 consists of the results and Chapter 4 consists of the discussion of the results. Finally, the conclusions and recommendation of the study is presented in Chapter 5.

Chapter 2: Methods

2.1 Study Country – Namibia

Namibia is located in the southwestern corner of Africa; bordered by Angola to the North, Botswana to the South-east, South Africa to the South and Zambia in the East (Figure 5.

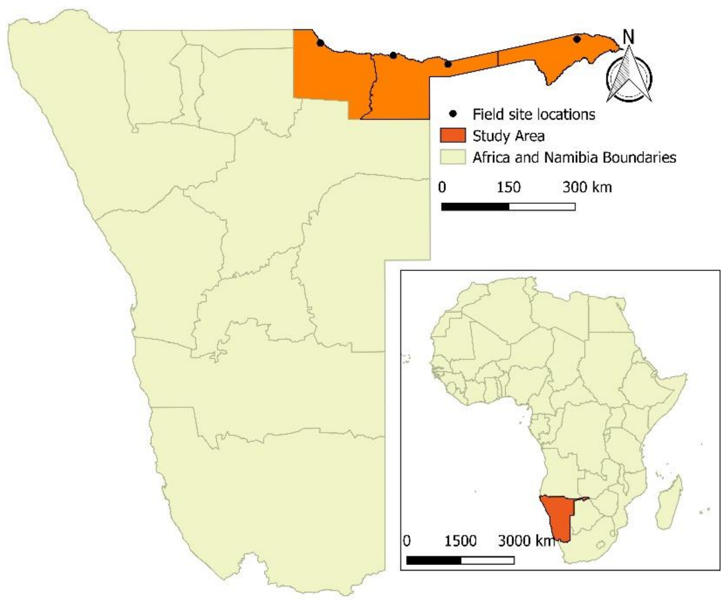

Figure 5: Namibia's position in Africa and the position of the study sites in Namibia (own compilation)

2.1.1 Study Regions

The study took place along a natural rainfall gradient across North-eastern Namibia. This area includes the Kavango East, Kavango West (referred to as the Kavango regions) and Zambezi regions (Figure 5). In Namibia, both Kavango and Zambezi regions fall under the tree savannah and woodland vegetation zones as per the classification in the preliminary vegetation map of Namibia (Giess 1971). Both of these regions are of high importance to populations of Namibia, both directly and indirectly. The Zambezi and Kavango regions together cover an area of 63,527 km^2 (Mendelsohn 2007). 16% of the Namibian population live in these two regions having a population density of 5.35 per km^2 which is double the national population density of 2.6 per km^2 (National Planning Commission 2013). The majority of the population in both areas live in rural areas and rely on the woodland resources for their livelihoods (both for own use and for income), thus creating a continuous demand for woodland resources (Leffers 2013). This includes wood products, such as firewood and poles, as well as non-timber forest products, such as seeds and medicinal tubers.

The Zambezi region lies at the lower elevation edge of the Kalahari Basin. As a result of this location there are only small patches of nutrient rich soils (Mendelsohn, 2007b). Most of the region must be extensively managed and fertilizers have to be applied to enable the production of higher crop yields in these nutrient poor sandy soils. In the sandy soils, *Pterocarpus angolensis*, *Baikiaea plurijuga*, *Guibourtia coleosperma*, *Burkea africana* and *Terminalia sericea* grow well creating a potential alternate source of income for the local communities. The only naturally high yield cropping, which is regionally still very poor, occurs on small patches of land that contain alluvial clays. Also, on these clayey soils, *Colophospermum mopane* grows well but many have been cut down for personal use (to make homestead fences, firewood, etc.). In comparison to regional cropping, yields are relatively low, but the crop yields in the Zambezi region are higher than most regions in the country (Mendelsohn and Roberts 1997). This has consequently led to this region being considered as ideal for large scale agricultural production. The situation is similar in the Kavango regions which is covered by mostly sandy, permeable and low-nutrient soils. There are only small concentrated areas along the Kavango river that allow for higher yield crop production. The extent of the potential arable land, is insufficient to provide a sustainable livelihood for most of the rural population in Kavango, even though this area has produced some of the larger, irrigated farming projects (Mendelsohn and el Obeid 2003). Although this may seem to solve an issue of poverty, the large scale unforeseen effects on the environment are either unknown or over looked. In order to make way for these irrigated farming projects, deforestation has to take place and water has to be extracted from the Okavango river which in itself has a very variable water flow.

Throughout the regions of Kavango West, Kavango East and Zambezi there are some key tree species which make a noticeable difference to the livelihoods of the populations living there. The species which will be focused on are *Pterocarpus angolensis* and *Burkea africana*. *Pterocarpus angolensis*, commonly called kiaat, is used commercially for timber production. *Burkea africana* is commonly used as poles or droppers for local homestead construction, but has started to be used commercially for timber construction. Both of these species are important, but are also being harvested at a high rate (TRAFFIC, 2015). *Burkea africana* is currently the most common tree species (De Cauwer, 2015b) found in these woodlands, representing about 29% of the canopy trees and 20% of the total basal area. *Pterocarpus angolensis* represents about 18% of the basal area (De Cauwer, 2015b).

2.1.2 Study Sites

The study tested the differences in the above and below ground carbon levels, of the two selected tree species, along the natural rainfall gradient from west to east in northern Namibia (Figure 6). Four sites (Nkurenkuru, Mashare, Divundu and Katima Mulilo) were chosen along this gradient in communal land areas. Nkurenkuru and Divundu have long-term average rainfall amounts (LTAR) between 600-650 mm, Mashare has a LTAR amount of 525-575 mm and Katima Mulilo has a LTAR amount of 675-700 mm. Although Nkurenkuru and Divundu had similar LTAR amounts, they were analysed separately, with the option for grouping together should they be seen to be statistically similar. Non-destructive measurements were taken at all four sites, and destructive measurements were taken at the Mashare site.

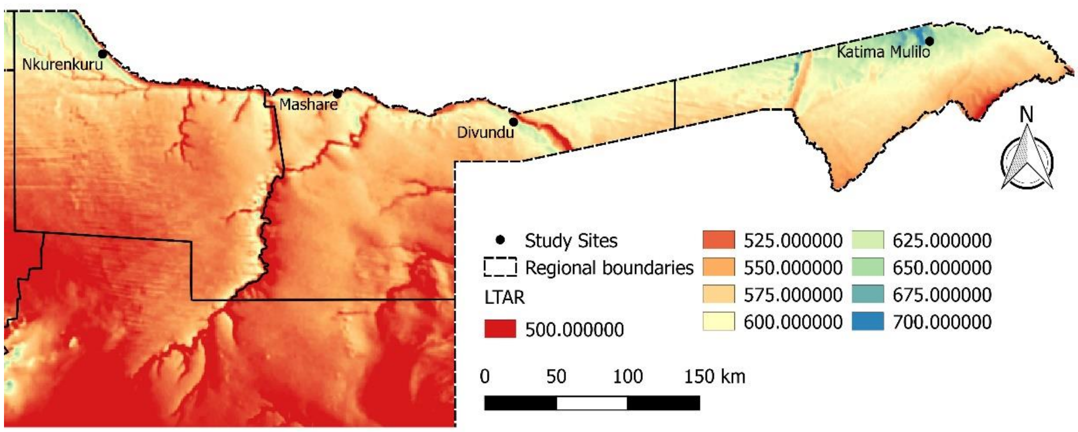

Figure 6: Location of study sites along the rainfall gradient showing long term average rainfall (LTAR) amounts in mm (LTAR data acquired from Karger et al., 2016)

2.2 Study Design

Through the literature search, two additional papers Ribeiro *et al.* (2011) and Ryan *et al.* (2011) were found to be the most useful in developing the research design. Both of these articles focussed on above and below ground carbon estimations. For this study, the above ground biomass specifically refers to all living biomass that is above the soil (including stems, stumps, branches, bark, seeds and foliage). The below ground biomass includes all living biomass of coarse living roots (thicker than 2 millimetres in diameter). The total organic carbon (or soil organic carbon/below ground carbon) includes all the organic material in the soil to a depth of 1 meter, but excluding the coarse roots of the above ground pools (USAID 2013).

Currently, there is no standardised methodology to assess carbon stocks across a landscape (Ribeiro *et al.* 2011 and Ryan *et al.* 2011). Since destructive harvesting is the most accurate way of determining the carbon storage in biomass, sample trees were selected in Mashare, where an agricultural deforestation project was already occurring, thus minimizing the impact of this study on the environment. The study design is presented in Figure 7.

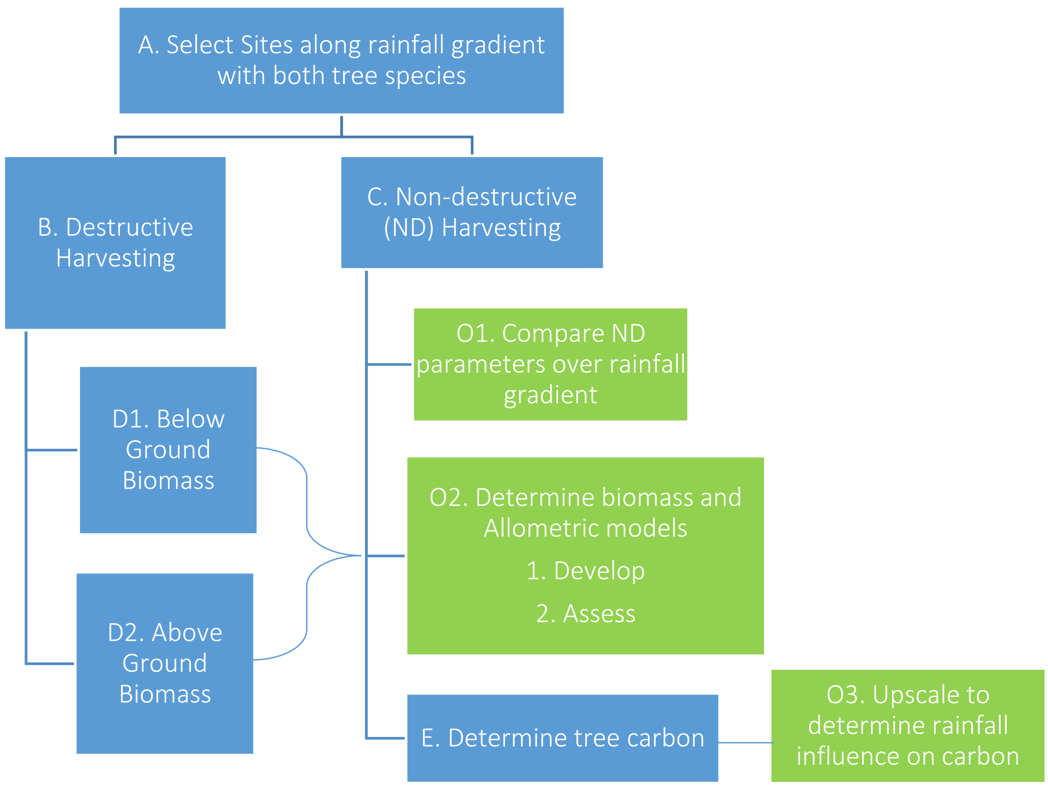

Figure 7: An outline of the different research steps required to complete the analysis. Blue defines analysis/progress steps and the green boxes identify research objective outputs.

2.3 Data Collection

In each of the four sites, at least forty trees of each species were selected, equally distributed over five diameter at breast height (dbh) classes. The trees were selected randomly in forest stands. The random selection of the trees allowed for a better representation of the area. Trees were then selected as per their diameter classes. A minimum of eight trees in each (dbh) class were measured. The dbh classes were: 5cm – 15cm, 15cm – 25cm, 25cm – 35cm, 35cm – 45cm (45 cm is the harvestable level for sawlogs in Namibia) and >45cm. The data sheets used can be seen in Appendix 1 and 2.

2.3.1 Above Ground Biomass – Destructive versus Non-destructive sites

At all four of the sites, non-destructive measurements were taken. These measurements did not cause any damage to the trees. In the non-destructive sites, no cutting of trees took place and only non-invasive measurements took place. These three non-destructive sites were located in Nkurenkuru, Divundu and Katima Mulilo although the non-destructive measurements were also taken at the Mashare (destructive) site. At the destructive site, trees were harvested to obtain the actual tree weight. Under normal circumstances, any harvesting of trees requires a permit from DoF and approval from the Namibian regional office. This was done in September 2016.

In Mashare, current deforestation work by the Ministry of Agriculture, Water and Forestry (MAWF), for an agricultural irrigation project, was piggy-backed on to serve as a site where trees could be destructively harvested and used in this study. This allowed the study to have a minimal impact on the harvesting of the two tree species. This is needed for the development of the allometric models in order to be able to calculate the tree biomass. The biomass figure is needed when developing the models in order to link the destructive harvesting output with the non-destructive parameters.

2.3.2 Above Ground Biomass – Field Data Collected at all sites

In the areas where there was no designated deforestation occurring, non-destructive measuring methods were used. At all four sites various non-destructive tree parameters were measured for each individual tree (Appendix 1 – data sheet). The data was collected from June to October 2016. These parameters and their units of measurement are outlined below:

- Tree height (in m) – the standing tree height was measured using a Vertex laser, which was taken as the measurement between the base of the stump and top of the tree (Figure 8). The distance from the tree (when using the Vertex laser) was dependent on the tree height as through the eye of the laser, the top of the tree should be visible. If a tree was already felled, a tape measure was used along the ground to measure height.
- Stem (or commonly referred to as bole) height (in m) – the stem height was measured using a tape measure, and was taken as the measurement of the distance from the base

of the stump to where the first branch branched off. If the stem was very high, the tape measure was attached to a pole in order to take this measurement.

- Stump diameter (in cm) – the stump diameter was measured using a tape measure and taken at 30 centimetres (cm) from the base of the stump
- Dbh (in cm) – the dbh was measured using a tape measure and taken at 1.3 metres from the base of the stump
- Diameter at each meter above dbh (in cm) – the diameter was measured using a Criterion laser fixed to a tripod, whereby the in-scope LED light offers an adjustable brightness level and projects a measurement bar scale that represents the subtended horizontal angle. This angular measurement and the horizontal distance to the target tree is used to calculate the diameter at each meter on the stem.
- Crown diameter (in cm) – both the major and minor axis of the canopy were measured using a tape measure. The measurement was made on the ground, with the crown edge was defined by a visual assessment of where the majority of the crown was present. Outlier branches were excluded from the measurement.
- Basal area – was measured using the dendrometer designed by the University of Goettingen. The main tree was aimed at dbh level and then a 360 degree turn was made, counting the number of stems which appear within each category on the dendrometer. The opening with the widest space corresponds to factor 1 to multiply the numbers of trees counted to get to the basal area per hectare. When a width of 2 or 4 is used, this is then multiplied by the number of trees counted in order to obtain the basal area per hectare. The dendrometer is held vertically at a distance of 50 cm from the eye.
- Bark thickness at stump diameter and dbh (in cm) – the bark thickness at stump diameter (30cm above the tree base) and dbh (1.3m) was measured using a pen knife which was inserted into the bark until the wood was reached (increased resistance), the thickness indicated on the knife was measured using a tape measure
- Disturbance – a visual assessment was done to determine if there had been any disturbance, what type and the class of disturbance (on a scale from 0 – 3, where 0 is no disturbance and 3 is severe disturbance)
- Phenology – a visual assessment was done to determine if the tree had leaves, was flowering/fruiting or had neither

Figure 8: Field tree height measurements taken with a Vertex laser

For all sites, the following additional measurements were recorded:

Soil Parameters (as in Figure 9): Soil colour and texture were also recorded at each sampled tree in each of the sites as per the Munsell (1992) Soil Charts. These measurements were taken within a 1 m radius of the main tree.

Figure 9: Example of a bole made to determine the soil colour and texture at the Nkurenkuru site

2.3.3 Above Ground Biomass – Field data collected at destructive site

For the destructive harvesting site, all of the non-destructive measurements were taken before any harvesting occurred. The 80 trees (40 per species) were then cut as close as possible to soil level (Figure 10).

Figure 10: Example of a tree cut close to soil level

After the tree was cut, the tree was divided into different sections. As per Brown (1997) and Alvarez *et al.* (2012), the tree was divided into stem, branches and twigs (Figure 11).

Figure 11: Example of a tree being divided into parts (stem, branches, twigs and roots)

After separation of the different parts of the tree, the fresh weights were taken using a 200 kilogram capacity hanging scale, which had an accuracy of 10 grams (Figure 12). For the larger parts (the stem and some branches), a chain saw was used to further divide the tree (Figure 13). The green weight of the entire tree was weighed in the field and not just parts/samples of it. This included twigs and branches of all sizes, as well as the stump. Some studies take the leaves into account for the above ground biomass, but as stated by Brown (1997), the leaves should not be considered permanent parts of the tree if they are deciduous species. Given that both species were deciduous, the leaves were not weighed.

Figure 12: Example of tree parts being weighed in the field

Figure 13: Example of tree being cut into pieces for weighing

Following field weighing, using a chain saw, wood disc samples were taken at stump, breast height, and stem (or bole) height and from two branches for trees with a height over 2.3 meters. For trees less than 2.5 meters tall, wood discs were taken at stump diameter, breast height, and at 2.3 meters. These wood discs were then weighed and labelled, and then brought to the laboratory for drying.

2.3.4 Below Ground Biomass

The below ground biomass was determined for the specifically harvested trees of Mashare. For each of the destructively harvested trees, the root systems were cut off as close to the stem as possible (Figure 14). A bulldozer (from the agricultural deforestation project) pushed down the harvested trees at the site. This pulled up the root systems and then the roots which were larger than two cm in diameter were followed and dug up. For some of the smaller trees, the root systems were dug up (Figure 15) and then cut off as close to the stump as possible. The root systems were dug up as widely as possible until the root itself was smaller than a two cm diameter. All of the roots were collected (up to a two cm diameter) and weighed in the field. For *B. africana*, the roots were dug up to depths of between 1 and 1.9 m, while for *P. angolensis* the roots were dug up between a depth of 1.8 and 2.8 m. This was done because most of the roots after these depths were not larger than two cm in diameter.

A sample of the roots from each harvested tree was then labelled immediately in the field (Figure 16). The samples were then brought to the laboratory for drying, as was done with the wood discs.

Figure 14: Example of root system being cut off a measured tree

Figure 15: Example of root system that was dug out

Figure 16: Example of the labelled root samples

2.3.5 Laboratory Analysis

From the Mashare site, all of the wood discs and root samples were brought to Windhoek for laboratory drying. A transport permit required by the Directorate of Forestry was obtained and can be seen in Appendix 3. All of the wood discs were placed in a drying oven (Figure 17) for at least 72 hours at a temperature of 105°C, ensuring that the weight stabilised. The weights of the discs were checked every day while in the oven to ensure that the weight actually stabilised. After the weight stabilised, the discs were weighed again to determine the wet to dry biomass ratio for each disc. The root samples were dried at 70°C until the weight stabilised. The wood discs required a higher temperature for drying than the root samples and as per Picard *et. al* (2012) the temperature was reduced to 70°C to not cause damage to the roots. After the weight stabilised, the root samples were weighed again to determine the wet to dry biomass ratio for each sample. The ratio was developed by dividing the dry weight by the wet weight.

Figure 17: Example of samples in the drying oven

2.3.6 Data Processing and Analysis

2.3.6.1 Data Exploration

Following the study design (Figure 7), R Statistical Software was used for the data processing and analysis. The summary of the data on tree variables is reported using measures of central tendency and dispersion including minimum, maximum, mean and standard deviation.

2.3.6.2 Compare whether rainfall results in statistically different non-destructive measurements in the tree species investigated.

In order to test the first hypothesis, of a significant difference in non-destructive tree parameters across the rainfall gradient, tests were performed using a One-Way ANOVA, followed by a Tukey HSD post-hoc test on the significant ANOVA tests. The post-hoc multiple comparisons test adjusts for inflation of probability of committing type I error (Picard *et al.* 2012). In order to ensure the models were done correctly, an analysis was conducted to ensure that parametric tests were the most relevant to run. This was done to ensure that there was a large enough sample size, since parametric tests are based on the validity of normality assumptions. For example, the ANOVA test requires normality of the residual error of the model or fairly large samples (n = > 50) so that the central limit theorem supports the validity of the results. This was done using the Anderson-Darling test (Picard *et al.* 2012). Since this condition was satisfied, there was no need to go for non-parametric tests especially given that the dependent variables are all continuous. Furthermore, non-parametric tests are less powerful compared to parametric tests and as such require larger samples for robust results. In addition, since one of the assumptions of the ANOVA test is that the variation is equal across the samples (homogeneity), Levene's test was run to ensure this.

In order to further test the first hypothesis on whether the tree measurements differed significantly across species and rainfall gradients (site), a two-way ANOVA was performed using the Generalised Linear Model (GLM) method. As a part of this GLM model, two main effects of species and sites and interaction of the sites and species were included. The sites were added in as a categorical variable. These analytical steps were reproduced for the third hypothesis to test whether rainfall influences woody biomass for either species, but this was only done once the allometric models were developed and fitted. To address assumption issues of linear modelling, the different predictor variables were evaluated for the degree of multicollinearity. The predictor variable pairs with high correlation were excluded in the models.

2.3.6.3 Develop and assess allometric models that link non-destructive tree measurements to above and below ground carbon values in Namibian woodlands.

For the second hypothesis of developing allometric models that link non-destructive tree measurements to above and below ground carbon values and assessing the developed allometric models to determine which produces the highest accuracy, allometric models were fitted to estimate the biomass using non-destructive measurements. These models were based on biomass figures extracted from the destructive measurements (above and below ground) and are estimated using multiple regression models.

To develop the allometric models for biomass, seven different forms of regression models were assessed from Picard *et al.* (2012). The log transformation of the biomass was used because it helped in resolving the issue of using non-normal biological data, as homoscedasticity is wanted. This means that the greater the tree biomass, the greater the variability of this biomass (Picard *et al.* 2012).

The various models tested are explained below and presented in Table 1. Model number 1 is based on the standard version of taking log D^2H as the independent variable, where D is the dbh and H is the tree height. Model number 2 is based on a general version with log DBH and log H as independent variables where H is the tree height. Model number 3 is based on combination of log D^2H and other parameters including log bark thickness at dbh, log crown diameter and log stump diameter. Model number 4 is based on only log bark thickness at dbh, log crown diameter and log stump diameter. Model number 5 is based on a reduced model using only log crown diameter and log stump diameter as predictor variables. Model number 6 is a model with log dbh, log D^2H, log bark thickness at dbh, log stump diameter and log crown diameter. Model number 7 is based on a general version with log DBH as the only independent variable.

Table 1: Allometric model forms applied to test whether non-destructive measures can be used to model tree biomass for Burkea africana and Pterocarpus angolensis

Model #	**Form**
1	$\text{Log(biomass)} = \beta_0 + \beta_1 \text{ Log } (D^2H) + \varepsilon$
2	$\text{Log(biomass)} = \beta_0 + \beta_1 \text{ Log(DBH)} + \beta_2 \text{ log(H)} + \varepsilon$
3	$\text{Log(biomass)} = \beta_0 + \beta_1 \text{ Log } (D^2H) + \beta_2 \text{ log (Bark thickness)} + \beta_3 \text{ log (Crown diameter)} + \beta_4 \text{ log (stump diameter)} + \varepsilon$
4	$\text{Log(biomass)} = \beta_0 + \beta_1 \text{ log (Bark thickness)} + \beta_2 \text{ log (Crown diameter)} + \beta_3 \text{ log (stump diameter)} + \varepsilon$
5	$\text{Log(biomass)} = \beta_0 + \beta_1 \text{ log (Crown diameter)} + \beta_2 \text{ log (stump diameter)} + \varepsilon$
6	$\text{Log(biomass)} = \beta_0 + \beta_1 \text{ Log } (D^2H) + \beta_2 \text{ log (DBH)} + \beta_3 \text{ log (Bark thickness)} + \beta_4 \text{ log (Crown diameter)} + \beta_5 \text{ log (stump diameter)} + \varepsilon$
7	$\text{Log(biomass)} = \beta_0 + \beta_1 \text{ Log (DBH)} + \varepsilon$

When modelling the destructive data, the Mashare dataset was split into a calibration and validation set to enable an independent assessment of the derived models. This involved a random split of 75% of the data set for calibration and 25% of the data set used for validation. The calibration dataset was used to run and develop the models and these were then assessed with the independent validation dataset. The seven models were tested on three different data sets, the combined above and below ground biomass, the above ground biomass only and the below ground biomass only. These models used the wet biomass of the tree.

For the allometric modelling, a linear regression model was fitted initially and RAMSEY's test for misspecification was performed to check the appropriateness of linear specification of the model. The measure of Akaike Information Criterion (AIC) was used to assess the trade-off between accuracy and complexity of the model. This statistic compares a group of models based on their goodness of fit and their simplicity, to compare what is lost through the inclusion of variables. The model reporting the lowest

AIC value was considered most quality. The coefficient of determination (adjusted R^2) and RMSE was also derived from the calibration and validation data sets. The most appropriate models were chosen by the lowest AIC value and the highest adjusted R^2 value for both the calibration and validation datasets. The selected models were then used to predict the biomass of individual trees at the non-destructive sites.

2.3.6.4 Determine whether rainfall influences woody biomass for either P. angolensis or B. africana.

The results from the allometric models were used to estimate biomass at the non-destructive sites across the rainfall gradient. The model used to estimate the biomass at the three ND sites as the fourth site had actual biomass figures measured. In order to test for the difference in biomass across rainfall gradient categories is done using ANOVA F test with Tukey's test used for Posthoc multiple comparisons test.

In the field, the wet biomass of the trees of Mashare was measured in the field. The wood discs and root samples were then oven dried to give a wet to dry biomass ratio. The average of these figures was then used to derive the above and below ground dry biomass of the complete tree, based on the average densities of the trees. The carbon stored in these trees can be estimated using the equation developed by the Alabama Forestry Commission, (2012) as they state the amount of carbon stored in the wood of most species is approximately 50% of the wood's oven dried weight:

Carbon Stored (kg) = Tree biomass x 0.5

Whereas the amount of carbon stored will need to be converted into tonnes of CO_2 (TC) as this is how it is reported in REDD+ and the UNFCCC. This was calculated per tree. This is converted by using the equation:

TC = Carbon content (in tonnes) x 3.67

In the equation above, 3.67 represents the quotient of 44 (the molecular mass of TC) and 12 (the atomic mass of the element carbon) (Trees for the Future 2007).

Chapter 3: Results

3.1 Introduction

This chapter presents the results of the carbon storage data collected across the rainfall gradient. This chapter is structured into 3 sections, based around the research questions. The GPS points for each of the trees measured and a map of these points can be found in Appendices 4 through 7.

For Mashare, there was no available data for basal area and disturbance due to the deforestation that had already occurred from the MAWF project. As per the Munsell (1992) Soil Charts, the soil at Mashare was classified as clayey sand for texture and had a soil colour of 6/6 in the hue 7.5 yr.

For Nkurenkuru, the average basal area for *B. africana* was 10.5 m^2/hectare and the composition were 36.9% *B. africana* and 21.2% *P. angolensis*. The average damage to the *B. africana* trees was 0.35 (with damage class 0 equalling no damage and damage class 1 equalling mild damage). For Nkurenkuru, the average basal area for *P. angolensis* was 11.3 m^2/hectare and the composition was 6.2% *B. africana* and 34.9% *P. angolensis*. The average damage to *P. angolensis* trees was 0.62. As per the Munsell (1992) Soil Charts, the soil at Nkurenkuru had two different classifications. One area was classified as loamy sand for texture and had a soil colour of 5/6 in the hue 2.5 yr. The other area was classified as sandy loam and had a soil colour of 6/2 in the hue 10 yr.

For Divundu, the average basal area for *B. africana* was 11.1 m^2/hectare and the composition was 41.7% *B. africana* and 22.2% *P. angolensis*. The average damage to the *B. africana* trees was 0.53. For Divundu, the average basal area for *P. angolensis* was 10.3 m^2/hectare and the composition was 8.3% *B. africana* and 60% *P. angolensis*. The average damage to *P. angolensis* trees was 0.53. As per the Munsell (1992) Soil Charts, the soil at Divundu was classified as clayey sand for texture and had a soil colour of 6/4 in the hue 7.5 yr.

For Katima Mulilo, *B. africana* the average basal area was 22.7 m^2/hectare and the composition was 38.2% *B. africana* and 18.8% *P. angolensis.* The average damage to the *B. africana* trees was 0.83. For Katima Mulilo, *P. angolensis* the average basal area was 22.8 m^2/hectare and the composition was 23.6% *B. africana* and 38.1% *P. angolensis*. The average damage to *P. angolensis* trees was 1.2. As per the Munsell (1992) Soil Charts, the soil at Katima Mulilo was classified as sand for texture and had a soil colour of 5/1 in the hue 7.5 yr.

3.2 Statistically compare non-destructive measurements in investigated tree species across a rainfall gradient

A comparison of the non-destructive measurement parameters for both of the investigated species (Table 2 and 3) showed that, as expected, *P. angolensis* (Table 3) is on average larger than *B. africana* (Table 2) for all of the measurements taken. From our results, it was seen that *B. africana* had tree heights on average between 5-10 m, with the tallest tree reaching a height of 13.4 m and the mean being 7.2 m. This is taller than Mannheimer and Curtis (2009) report.

Table 2: Descriptive statistics of the non-destructive tree measurements recorded at the 4 different field sites, for Burkea africana, across the rainfall gradient

Parameter (measurement unit)	N*	Minimum	Maximum	Mean	SD[a]
Height (m)	175	2.00	13.40	7.24	2.50
DBH (cm)	175	5.10	63.06	25.32	13.83
Bark thickness at DBH (cm)	175	0.20	2.00	1.07	0.42
Stump diameter (cm)	175	6.05	61.78	28.83	14.40
Bark thickness at stump (cm)	175	0.60	2.20	1.07	0.46
Crown diameter (cm)	175	40.00	1640.00	690.69	330.41
Stem diameter at 2.3m (cm)	158	1.00	52.60	24.45	13.03
Stem diameter at 3.3m (cm)	148	0.30	52.00	22.23	11.62
Stem diameter at 4.3m (cm)	137	1.00	51.80	19.83	11.37
Stem diameter at 5.3m (cm)	127	0.50	51.00	16.68	11.81
Stem diameter at 6.3m (cm)	105	1.00	48.00	14.87	11.75
Stem diameter at 7.3m (cm)	77	0.10	42.10	13.63	10.79
Stem diameter at 8.3m (cm)	47	0.50	27.60	10.97	8.69

**N= the number of samples*

[a] SD= standard deviation

For *P. angolensis*, the average tree heights ranged between 7-12 m, with the tallest tree reaching a height of 16.2 m, and the mean being 7.95 m. The dbh averaged 28.19 cm with the broadest tree having a diameter of 92.37 cm. This is considerably larger than expected for the tree heights reported.

Table 3: Descriptive statistics of the non-destructive tree measurements recorded at the 4 different field sites, for Pterocarpus angolensis, across the rainfall gradient

Parameter (measurement unit)	N	Minimum	Maximum	Mean	SD
Height (m)	172	1.70	16.20	7.95	2.88
DBH (cm)	172	4.46	92.36	28.19	16.77
Bark thickness at DBH (cm)	172	1.00	5.40	1.75	0.69
Stump Diameter (cm)	172	5.73	97.13	32.14	18.0
Bark thickness at Stump (cm)	172	0.00	4.20	1.71	0.59
Crown diameter (cm)	172	90.00	2060.00	792.05	445.78
Stem diameter at 2.3m (cm)	157	2.10	60.10	26.32	14.47
Stem diameter at 3.3m (cm)	152	0.20	55.40	23.71	13.91
Stem diameter at 4.3m (cm)	140	0.30	49.80	21.87	12.97
Stem diameter at 5.3m (cm)	125	2.10	46.30	20.10	12.22
Stem diameter at 6.3m (cm)	115	0.30	42.10	17.13	11.90
Stem diameter at 7.3m (cm)	93	0.10	38.40	16.24	10.54
Stem diameter at 8.3m (cm)	73	0.50	36.20	13.76	9.55

Table 4 and 5 report the summary of the results of the one-way ANOVA F test for the comparison of the tree measurements across the rainfall gradient as well as Tukey's post-hoc multiple comparison tests. In the instance where there was a zero value, it was replaced with 'NA' during the analysis to ensure there was no bias. *B. africana* (Table 4) showed that for all of the characteristics measured, a significant difference is reported. For the sites of Nkurenkuru and Divundu, which have similar LTAR, a significant difference was only seen when looking at the stem diameters above 4.3 m. Therefore, these two sites could have been grouped during the analysis since the important parameters did not show a significant difference. In addition, the shape of the stem changes across the rainfall gradient by the high R^2 values for the stem diameters over 4.3 m. With regards to the rainfall gradient, the significant parameters are dbh, stump diameter and the stem diameter at 2.3m. These show some evidence of a rainfall gradient being present. The other parameters did not show a specific site difference.

Overall, rainfall does have a significant effect on the tree measurements that were taken and the alternate hypothesis of objective 1 can be accepted.

Table 4: ANOVA F Test based comparison of tree characteristics across sites for Burkea africana

Parameter (measurement unit)	Site[a]	Mean	Adj. R^2	RMSE	F[b]	Tukey's HSD[b]
Bark thickness at DBH (cm)	MA	1.20	0.36	0.40	33.76 ***	(KM, D) *** (MA, D) *** (NK, KM) *** (NK, MA) *** (MA, KM) **
	D	0.79				
	NK	0.65				
	KM	1.40				
Bark thickness at Stump (cm)	MA	1.16	0.33	0.44	29.3 ***	(KM, D) *** (MA, D) *** (NK, KM) *** (NK, MA) *** (MA, KM) * (NK, D) *
	D	0.83				
	NK	0.60				
	KM	1.41				
Crown Diameter (cm)	MA	637.20	0.03	325	2.94 *	(KM, D) * (NK, KM) *
	D	763.52				
	NK	750.52				
	KM	590.63				
DBH (cm)	MA	18.47	0.08	13.28	5.89 ***	(MA, D) * (NK, MA) ** (MA, KM) ***
	D	25.69				
	NK	26.38				
	KM	30.64				
Stump Diameter (cm)	MA	20.88	0.10	13.68	7.29 ***	(MA, D) ** (NK, KM) ** (MA, KM) ***
	D	29.11				
	NK	30.42				
	KM	34.68				
Height (m)	MA	6.34	0.06	2.42	4.72 ***	(KM, D) * (MA, D) ** (NK, MA) ***
	D	8.09				
	NK	7.64				
	KM	6.72				
Stem Diameter at 2.3m (cm)	MA	15.53	0.11	12.25	7.51 ***	(MA, D) ** (NK, MA) *** (MA, KM) ***
	D	23.28				
	NK	22.8				
	KM	26.78				
Stem Diameter at 3.3m (cm)	MA	12.50	0.12	10.85	7.62 ***	(MA, D) ** (NK, MA) *** (MA, KM) **
	D	19.64				
	NK	22.20				
	KM	20.33				
Stem Diameter at 4.3m (cm)	MA	8.93	0.26	9.69	17.42 ***	(MA, D) *** (NK, D) ** (NK, MA) *** (NK, KM) *** (MA, KM) **
	D	16.43				
	NK	20.99				
	KM	14.76				

Stem Diameter at 5.3m (cm)	MA	5.49	0.44	8.78	34.52 ***	(KM, D) ** (NK, D) *** (NK, KM) *** (NK, MA) *** (MA, D) ***
	D	12.84				
	NK	19.51				
	KM	9.14				
Stem Diameter at 6.3m (cm)	MA	2.57	0.56	7.72	45.58 ***	(KM, D) ** (NK, D) *** (NK, KM) *** (NK, MA) *** (MA, D) ***
	D	9.31				
	NK	17.17				
	KM	4.98				
Stem Diameter at 7.3m (cm)	MA	0.97	0.68	5.99	56.41 ***	(KM, D) ** (NK, D) *** (NK, KM) *** (NK, MA) *** (MA, D) **
	D	6.01				
	NK	13.36				
	KM	2.19				
Stem Diameter at 8.3m (cm)	MA	0.31	0.72	4.49	40.8 ***	(NK, D) *** (NK, KM) *** (NK, MA) ***
	D	3.30				
	NK	6.42				
	KM	0.87				

[a] D = Divundu (Medium rainfall), MA = Mashare (Low rainfall), KM = Katima Mulilo (High rainfall) and NK = Nkurenkuru (Medium rainfall)
[b] Significance levels for the tests are *** = .001, ** = .05, * = .01 and ns = non-significant

Results for *P. angolensis* (Table 5) indicate that bark thickness at DBH and bark thickness at stump do not report any significant difference across the rainfall gradient. For all of the other characteristics, significant effect of rainfall is reported (p = < .05). For the Nkurenkuru site, the bark thickness at the stump was relatively low considering the bark thickness at dbh. At this site, there was a lot of disturbance due to termites at the stump and this would influence the results. As in with *B. africana*, in the Katima Mulilo site the largest dbh values were seen. Also, there were many trees with broken off tops in this area. In the Divundu site, the soil type was a clayey soil as per Munsell (1992) Soil Charts whereas the other sites had much sandier soil.

For *P. angolensis,* these results indicate that the alternate hypothesis of significant effect of rainfall on tree measurements is supported for all measurements except bark thickness. The stem diameters above 5.3 m are the best indicators to model the differences in rainfall.

Table 5: ANOVA F Test based comparison of tree characteristics across sites for Pterocarpus angolensis

Parameter (measurement unit)	Site	Mean	Adj. R^2	RMSE	F	Tukey's HSD
Bark thickness at DBH (cm)	MA	1.60	0.02	0.78	2.12 **	(NK, D) **
	D	1.48				
	NK	1.88				
	KM	1.63				
Bark thickness at Stump (cm)	MA	1.56	-0.01	0.70	0.43 ns	
	D	1.55				
	NK	1.69				
	KM	1.65				
Crown Diameter (cm)	MA	767.62	0.04	437.8	3.09 **	(KM, D) **
	D	901.30				
	NK	850.53				
	KM	629				
DBH (cm)	MA	21.24	0.04	16.43	3.39 **	(MA, D) ** (MA, KM) ** (NK, MA) **
	D	29.51				
	NK	30.82				
	KM	31.05				
Stump Diameter (cm)	MA	23.78	0.06	17.54	4.34 ***	(MA, D) *** (MA, KM) *** (NK, MA) ***
	D	36.23				
	NK	34.39				
	KM	33.79				
Height (m)	MA	7.32	0.07	2.78	5.14 ***	(KM, D) *** (MA, D) ** (NK, KM) **
	D	8.94				
	NK	8.50				
	KM	6.89				
Stem Diameter at 2.3m (cm)	MA	17.92	0.06	14.06	4.62	(MA, D) *** (NK, MA) *
	D	24.13				
	NK	27.63				
	KM	25.98				
Stem Diameter at 3.3m (cm)	MA	14.58	0.10	13.21	6.88 ***	(MA, D) *** (NK, MA) *** (NK, KM) *
	D	21.17				
	NK	26.81				
	KM	20.56				
Stem Diameter at 4.3m (cm)	MA	11.4	0.14	12.06	8.70 ***	(KM, D) ** (MA, D) *** (NK, KM) *** (NK, MA) ***
	D	18.12				
	NK	25.78				
	KM	14.96				
Stem Diameter at 5.3m (cm)	MA	15.32	0.33	10.05	20.8 ***	(KM, D) ** (MA, D) *** (NK, D) ** (NK, KM) *** (NK, MA) ***
	D	8.08				
	NK	23.65				
	KM	10.51				

Stem Diameter at 6.3m (cm)	MA	5.17	0.38	9.34	24.74 ***	(KM, D) ** (MA, D) *** (NK, D) *** (NK, KM) *** (NK, MA) ***
	D	11.95				
	NK	21.15				
	KM	6.59				
Stem Diameter at 7.3m (cm)	MA	3.26	0.38	8.329	19.49 ***	(MA, D) ** (NK, D) *** (NK, KM) *** (NK, MA) ***
	D	9.37				
	NK	17.57				
	KM	4.02				
Stem Diameter at 8.3m (cm)	MA	2.15	0.50	6.77	24.75 ***	(NK, D) *** (NK, KM) *** (NK, MA) ***
	D	6.09				
	NK	12.37				
	KM	2.11				

[a] D = Divundu, MA = Mashare, KM = Katima Mulilo and NK = Nkurenkuru
[b] Significance levels for the tests are *** = .001, ** = .05, * = .01 and ns = non-significant

Table 6 reports on the summary of the results of a two factor ANOVA, taking both site and species into account and the interaction of sites and species. For all of the parameters, both site and species were significant to explaining the models. For many of these parameters including the information of site and species explain less than 30% of the variability observed in these parameters. Only crown diameter had 65% of the variability explained by this interaction. Only bark thickness at DBH and bark thickness at stump reported significant interaction effect of site and species (p = <.05). This indicates that difference across sites is not same across two species or equivalently, the difference in the two species is not similar for the sites for bark thickness at breast and stump height. Other tree characteristics' measurements did not report significant interaction of site and species. This does make it easier when developing the models as these interactions do increase the complexity of the models.

Table 6: ANOVA F Test Based Comparison of tree characteristics across sites and species

Parameter (measurement unit)	Overall F[a]	Site	Individual F[a]	Adj. R^2	RMSE
Bark thickness at DBH (cm)	21.78 ***	Site	6.33 ***	0.30	0.62
		Species	100.09 ***		
		Site * Species	11.12 ***		
Bark thickness at stump height (cm)	22.10 ***	Site	8.34 ***	0.30	0.58
		Species	102.26 ***		
		Site * Species	9.13 ***		

Crown Diameter (cm)	3.47 ***	Site	5.75 ***	0.65	385.10
		Species	6.17 *		
		Site * Species	0.29 ns		
DBH (cm)	4.22 ***	Site	8.42 ***	0.06	14.92
		Species	3.4 ns		
		Site * Species	0.30 ns		
Stump Diameter (cm)	5.25 ***	Site	9.97 ***	0.08	15.71
		Species	4.07 *		
		Site * Species	0.93 ns		
Height (m)	5.19 ***	Site	9.45 ***	0.08	2.61
		Species	6.72 **		
		Site * Species	0.40 ns		
Stem diameter at 2.3m (cm)	5.23 ***	Site	11.24 ***	0.09	13.18
		Species	1.38 ns		
		Site * Species	0.49 ns		
Stem diameter at 3.3m (cm)	6.29 ***	Site	13.32 ***	0.13	12.1
		Species	1.17 ns		
		Site * Species	0.97 ns		
Stem diameter at 4.3m (cm)	10.66 ***	Site	23.39 ***	0.2	10.95
		Species	1.66 ns		
		Site * Species	0.93 ns		
Stem diameter at 5.3m (cm)	24.15 ***	Site	53.34 ***	0.39	9.42
		Species	7.35 **		
		Site * Species	0.57 ns		
Stem diameter at 6.3m (cm)	28.8 ***	Site	64.93 ***	0.47	0.86
		Species	4.03 *		
		Site * Species	0.92 ns		
Stem diameter at 7.3m (cm)	27.51 ***	Site	60.53 ***	0.52	7.36
		Species	5.53 *		
		Site * Species	1.81 ns		
Stem diameter at 8.3m (cm)	24.22 ***	Site	53.45 ***	0.58	5.99
		Species	7.88 **		
		Site * Species	0.43 ns		

[a] Significance levels for the tests are *** = .001, ** = .05, * = .01 and ns = non-significant

3.3 Develop and assess allometric models that link non-destructive tree measurements to above and below ground carbon values in Namibian woodlands.

To develop the allometric models for biomass, seven different forms of regression models were assessed from Picard *et al.* (2012). These models are shown in Table 1. The model coefficients can be found in Appendices 8 through 10. Bark thickness at stump is not included in any model as it is highly correlated (r = > 0.9) with other predictor variables and hence, including the variable would inflate the standard error of estimates of coefficients in the regression model. Table 7, 8 and 9 show the assessment of the allometric models. The models were applied to the combined above and below ground, and then to these two factors separated. It was investigated to see whether these parameters can be used to assess biomass, if not for the entire tree, then at least for the above ground component, and potentially the below ground component. The findings presented in these tables are discussed in further details in the two sub-sections below which address the interpretations based on each species. The highlighted values in the tables show the models which are the most appropriate to be fitted to the non-destructive sites. These models were chosen by having the lowest AIC values and the highest R^2 values.

Table 7: Assessment of the total biomass allometric models developed from the destructive harvesting sampling conducted in Mashare for Burkea africana and Pterocarpus angolensis

	Model Number	Cal. R^2	Cal. RMSE	Val. R^2	Val. RMSE	AIC
Burkea africana	1	0.32	0.46	0.75	0.31	42.10
	2	0.31	0.46	0.61	0.32	43.64
	3	0.38	0.44	0.53	0.30	42.15
	4	0.40	0.43	0.53	0.30	40.15
	5	0.37	0.44	0.68	0.30	40.69
	6	0.38	0.44	0.60	0.30	42.88
	7	0.33	0.45	0.68	0.31	41.73
Pterocarpus angolensis	1	0.65	0.38	0.52	0.47	32.35
	2	0.64	0.38	0.81	0.50	33.57
	3	0.67	0.37	0.83	0.48	32.73

	4	0.68	0.37	0.84	0.48	31.30
	5	0.36	0.69	0.86	0.48	29.50
	6	0.66	0.37	0.79	0.52	34.43
	7	0.66	0.67	0.82	0.49	31.59

Table 8: Assessment of the above ground biomass allometric models developed from the destructive harvesting sampling conducted in Mashare for Burkea africana and Pterocarpus angolensis

	Model Number	Cal. R^2	Cal. RMSE	Val. R^2	Val. RMSE	AIC
Burkea africana	1	0.81	0.69	0.77	0.62	66.61
	2	0.81	0.69	0.71	0.65	67.55
	3	0.84	0.63	0.85	0.54	63.87
	4	0.85	0.62	0.85	0.54	61.92
	5	0.85	0.61	0.88	0.51	60.46
	6	0.85	0.62	0.79	0.60	63.81
	7	0.82	0.68	0.70	0.66	65.56
Pterocarpus angolensis	1	0.77	0.82	0.78	0.53	79.28
	2	0.77	0.82	0.82	0.47	80.56
	3	0.80	0.77	0.80	0.49	78.61
	4	0.80	0.76	0.80	0.49	76.62
	5	0.79	0.80	0.80	0.49	78.01
	6	0.79	0.79	0.80	0.49	63.81
	7	0.78	0.81	0.82	0.46	65.56

Table 9: Assessment of the below ground biomass allometric models developed from the destructive harvesting sampling conducted in Mashare for Burkea africana and Pterocarpus angolensis (ns= non-significant)

Below Ground Biomass	Model Number	Cal. R^2	Cal. RMSE	Val. R^2	Val. RMSE	AIC
Burkea africana	1	ns				
	2	ns				
	3	ns				
	4	ns				
	5	ns				
	6	ns				
	7	ns				

Pterocarpus angolensis	1	ns				
	2	ns				
	3	0.25	0.33	0.07	0.54	26.48
	4	0.28	0.33	0.07	0.54	24.48
	5	0.28	0.33	0.10	0.54	23.78
	6	0.23	0.34	0.10	0.53	28.42
	7	ns				

As seen in Table 9, none of the models showed significance in modelling *B. africana*, while only four of the seven models showed significance for *P. angolensis*. This shows that below ground biomass modelling for these species is not accurate and not significant to keep in the models for total biomass.

3.3.1 Allometric models for *Burkea africana*

Table 7 indicates that none of the R^2 values were above 0.5 when including the total biomass of the tree. Therefore, none of these models met the objective 2 hypothesis requirement of being able to model total biomass with an accuracy above 70% (or uncertainty level below 30%). However, when looking at just the above ground biomass models (Table 8), all of the models can explain more than 70% of the variability in biomass. Model 5 was chosen as the best fit as this has the highest R^2 value of 0.8497 and the lowest AIC value of 60.4551. Table 10 reports on the correlation matrix of variables for *B. africana* species from the Mashare site data. Crown diameter and height have a high correlation of 0.938 as well as dbh and stump diameter. This matrix adds evidence as to why the model in Table 7 was chosen.

Table 10: Correlation matrix of variables for Burkea africana for Mashare

	Bark thickness DBH	**Crown diameter**	**DBH**	**Height**	**Stump diameter**
	1.00				
Crown diameter	0.29	1.00			
DBH	0.21	0.79	1.00		
Height	0.21	0.94	0.86	1.00	
Stump Diameter	0.21	0.84	0.97	0.88	1.00

3.3.2 Allometric models for *Pterocarpus angolensis*

Table 7 indicates that none of the R^2 values were above 0.7 when including the total biomass of the tree. Therefore, none of these models met the objective 2 hypothesis requirement of being able to model total biomass with an accuracy above 70% (or uncertainty level below 30%). This was the same situation as with *B. africana*. However, when looking at just the above ground biomass in Table 8, all of the models can explain more than 70% of the variability in biomass. Model number 6 was chosen as most appropriate because it had the lowest AIC value of 63.8056 and the third highest R^2 value of 0.7884. Table 11 reports on the correlation matrix of variables from the Mashare site data. Crown diameter and height have the highest correlation of 0.899, while crown diameter and dbh as well as stump diameter show high correlation as well. This matrix adds evidence as to why the model in Table 7 was chosen.

Table 11: Correlation matrix of variables for Pterocarpus angolensis for Mashare

	Bark thickness at DBH	**Crown diameter**	**DBH**	**Height**	**Stump diameter**
	1.00				
Crown diameter	0.59	1.00			
DBH	0.58	0.90	1.00		
Height	0.62	0.90	0.86	1.00	
Stump Diameter	0.55	0.85	0.97	0.82	1.00

3.4 Biomass and Total Carbon Values for All Sites

Table 12 shows the mean biomass of all forty trees per site and mean total carbon values of all forty trees per site for all of the sites for *B. africana* and *P. angolensis* as calculated with the selected models applied using the non-destructive parameters. These represent an average biomass value at the individual tree scale, and not per plot. These models were chosen based on the models which had the highest adjusted R^2 values and the lowest AIC values in Section 3.3. Modelling for the below ground biomass was not done as there is too much uncertainty with these models with either no significance or R^2 values above 0.7, i.e. none of the models could explain more than 70% of the variability in the below ground biomass.

From these results, it shows that sites influence the tree biomass and the total carbon stored in the trees. For all of the models, Mashare (with the lowest LTAR) has the lowest values for biomass and total carbon while Katima Mulilo (with the highest LTAR) has the highest values for biomass and total carbon. It is interesting that for most of the sites the mean total biomass values are lower than the values that only take into account the above ground biomass. This could mean that including the below ground biomass causes the models to under estimate the tree biomass. For the Mashare site, the predicted biomass values were used as the measured biomass values were used in order to create the models.

Table 12: Mean biomass and total carbon values for all forty trees across all sites along the rainfall gradient

Species	Variable	Model #	Site	Mean Biomass (tonnes)	Mean Total Carbon (tonnes)	Adj. R^2	RMSE	F	Tukey's HSD
Burkea africana	Total biomass	5				0.21	1131	16.05 ***	(KM, D) *** (MA, D) ** (MA, KM) *** (NK, KM) *** (NK, MA) ***
			D	2.20	0.004				
			MA	2.12	0.004				
			NK	2.93	0.005				
			KM	3.85	0.007				
Burkea africana	Above ground biomass	5	MA	0.85	0.002	0.12	2809	8.67 ***	(KM, D) ** (MA, D) ** (MA, KM) *** (NK, MA) ***
			D	2.31	0.004				
			NK	3.16	0.006				
			KM	3.83	0.007				
Pterocarpus angolensis	Total biomass	4	MA	1.69	0.003	0.03	1475	2.96 **	(MA, D) **
			D	2.08	0.004				
			NK	2.04	0.004				
			KM	1.08	0.002				
Pterocarpus angolensis	Above ground biomass	6	MA	0.97	0.002	0.03	2206	2.65 **	(MA, D) ** (NK, MA) *
			D	2.21	0.004				
			NK	2.00	0.004				
			KM	1.92	0.004				

[a] D = Divundu, MA = Mashare, KM = Katima Mulilo and NK = Nkurenkuru
[b] Significance levels for the tests are *** = .001, ** = .05, * = .01 and ns = non-significant

Chapter 4: Discussion

4.1 Introduction

This chapter discusses the results presented in chapter three and will focus on the research objectives, namely, the statistically important measurements of trees, biomass and carbon calculations, the relationship of a rainfall gradient on these calculations and the allometric models developed.

4.2 Research Objective 1

Research objective number 1 investigated whether rainfall results in statistically different non-destructive measurements in the tree species investigated. Objective 1 allows to determine if stem shape changes along the sites, which was proven.

4.2.1 *Burkea africana*

For *B. africana*, all of the tree parameters differed statistically across the sites (as shown in Table 4). This is significant because it shows that the trees do respond differently to amounts in rainfall (as per the different sites) and respond as expected where the larger values occurred in the higher rainfall areas. This is specifically important for measurements such as tree height and dbh as these are often used as the input measurements in allometric models to determine carbon storage. Although, tree height did not follow this trend. For these sites, Mashare had the lowest values and Katima Mulilo had the highest values. This is what was expected as these two have the lowest LTAR and highest LTAR respectively. For instance, dbh increased with mean rainfall, from 18.5 cm at the Mashare site to 30.6 cm at the Katima Mulilo rainfall site. This trend was also followed for Nkurenkuru and Divundu.

In the Katima Mulilo site, the largest dbh values were seen but the crown diameter and heights were not as expected. The mean crown diameter and the height values were smaller than for the other sites. Since this is the site with the highest LTAR, it was expected that these values would be the highest. This site had the densest woodland cover of all of the sites from personal observation, and this could explain why the crown diameters were smaller, but not the tree height component. It would be of interest to include the basal area component in the modelling as this may also explain this difference. Increased competition could cause the crown diameters to be smaller. It was also observed that many of the tops of the crowns of these trees were broken off. This could be due to competition for the space.

4.2.2 *Pterocarpus angolensis*

For *P. angolensis*, all of the tree parameters except bark thickness (at stump and dbh) differed statistically across the rainfall gradient (as shown in Table 5). This is also significant because it shows that the trees do respond differently to amounts in rainfall, as with *B. africana*. For example, the dbh increased with mean rainfall from 21.24 cm at the Mashare site (with the lowest LTAR) to 31.05 cm at the Katima Mulilo site (with the highest LTAR). The sites of Nkurenkuru and Divundu also follow this trend. The difference between these two species is that the thickness of the bark on the *P. angolensis* trees do not seem to change throughout the rainfall gradient. There are a few possibilities as to why the bark thickness does not significantly differ across the gradient. Mannheimer *et al.* (2009) stated that the tree can withstand large forest fires, thus allowing the tree to die back to its main stem and then recoppice the next year. This would in turn burn off the bark from the main stem of the tree and allow for the bark to grow back the next year (Caro *et al.* 2005). Since the woodlands in Namibia are quite sparsely populated (Mendelsohn and el Obeid 2005), then there would be less livestock and grazing. There would be potentially increased fuel load and thus the opportunity for hotter fires which could cause critical increase in the temperature conditions in the floor of the woodlands. This could cause an increase in fire damage to these trees which would influence the bark behaviour seen (Colgan *et al.* 2014).

From personal observations at the sites, the bark of the *P. angolensis* tree is able to be removed very easily. Many of the trees observed had human interference where the bark was removed, or the trees were cut in order to show the 'blood' sap which comes from the tree. This seems to be attributed to the curiosity of the children in the region, as picking off the bark and allowing the 'blood' sap to run out has offered them some entertainment, as per the personal conversations had with the local communities while conducting the research.

As with *B. africana,* the Katima Mulilo site, the mean crown diameter and the height values were smaller than for the other sites. Since this is the site with the highest LTAR, it was expected that these values would be the highest. This site had the densest woodland cover for all of the sites (Chakanga 1995), and this could explain why the crown diameters were smaller. Larger competition could cause the crown diameters to be smaller. In the Divundu site, the soil type was a clayey soil as per Munsell (1992) Soil Charts whereas the other sites had much sandier soil. This could have influenced the higher height values seen in the area and an indication that this soil type allows for better growth.

As Moses (2013) states, *P. angolensis* is a very high valued timber species locally and trees are selectively chosen for harvesting. The selective harvesting practices provide an increase in income for the locals, but it has a negative effect on the woodlands of Namibia (Chakanga 2003). Also, this selective harvesting could possibly cause bias in the data as many of the larger and attractive trees have already been cut down for timber usage (Kamwi *et al.* 2015).

4.2.3 Rainfall vs Sites vs Rainfall and Sites

When comparing both rainfall and sites and the interaction between rainfall and sites, it was shown that the difference across the rainfall gradient is not the same across the two species (as shown in Table 6). This indicates that the differences in rainfall at each of the sites does not have the same effect on both of the species. Therefore, there are other factors which are influencing their growth and measurements. This could be attributed to different tree densities and basal area in the areas, such as *B. plurijuga* populations in the area (De Cauwer *et al.* 2016) or the abundance of fires in the region that have affected the amount of seeds for regeneration (Kayofa 2015) or even the selective harvesting (Moses 2013). Fires are a stress factor which can, for example, decrease the height that can be reached, which is the same for poor soils (Henry *et al.* 2011). Typically, trees remain shorter in stressed environments and because of this their tree shape can also change (Alvarez *et al.* 2012). The tree shape changes a lot throughout the different sites. Trees are also competing with other trees and shrubs for light and water (Chakanga 2000) which causes stress and possible shorter heights.

4.3 Research Objective 2

Research objective number 2 looked at developing and comparing different allometric models that link non-destructive measurements of trees to above and below ground carbon values, to determine which produces an accuracy below the 30% uncertainty level.

4.3.1 *Burkea africana*

For *B. africana,* when taking into account total biomass, none of the models meet the 30% uncertainty level. This would be modelling both the above and below ground biomass, where there is little data available for the root structures and below ground biomass models. Although the root systems were dug up and weighed in the field, there could have been issues in possibly not digging up all of the root system and this could cause the lack of certainty in the models. This has also been seen in other forest areas (Ribeiro *et al.* 2011) as a difficult measurement to make and develop accurate models to estimate below ground biomass. Most of the studies that assess the belowground biomass focus on the upper layers, which was done in this study, due to the inherent difficult of measuring root system (Beets *et al.* 2012). Usually tree height and dbh are two good indicators of the biomass in trees (Angombe 2004; Ministry of Environment and Tourism 1995), but this was not shown for these total biomass models.

Although, when looking at just above ground biomass, model number 5 is deemed the most appropriate. This model includes more complicated measurements that would make it difficult for Namibian foresters to take these in the field with the proper accuracy needed. Expert and constant training would need to be done to ensure that the foresters are taking the correct measurements. The simpler the methods and measurements taken, the easier it will be to incorporate this into a Namibian forestry field data collection report (Ministry of Agriculture, Water and Forestry 2011). It would be possible to look at using model number 7, which only takes into account the dbh measurement of the tree. Using this model, you lose a 3% accuracy in the outcomes, but this would be easier for foresters to use in the field.

Unfortunately, this means that there is not an allometric model that will link the non-destructive measurements of the trees to above and below ground carbon within the 30% uncertainty level presented by REDD+. It is possible to address this by having regional equations for the trees, but more research will need to be done. This is not the ideal scenario for Namibia, as it means that for *B. africana*, which is a species of high importance and has a high basal area percentage (De Cauwer *et al.* 2016), non-destructive measurements are not a good indicator of the carbon stored by these trees. This could be attributed to their shallow root system of only two m (De Cauwer *et al.* 2016) or even the large amount of competition. Although soil structure, geology of the land and underground water systems may also be an explanation. From personal observations in the field, it was found that when *B. plurijuga* was in high abundance that *B. africana* was then in very low abundance which was supported by research done by De Cauwer *et al.* (2016). This could also be attributed to the fact that *B. africana* is more an early succession species which *B. plurijuga* likes more stable conditions (De Cauwer *et al.* 2016). Based on the environmental factors in the field, *B. africana* is affected largely by the herbaceous and tree cover (Kabajani 2016). This would mean that it would be important to capture this information and see if this can contribute and improve the modelling process.

Although, these results do not make it easier for the Namibian forestry officials to estimate the carbon storage of this tree, it is possible to destructively harvest a few trees in each dbh class for the non-destructive sites in this study, which would provide actual biomass values for the areas of different LTAR. This would mean that more than 40 trees would need to be felled in an area to provide greater accuracy for the model. This could allow additional information to be brought into the models, which in turn could allow them to have less than 30% uncertainty. Throughout all of the sites, communal areas were chosen with no protection status (for example not a community forest either), and this could have affected the data collected. In these areas, which are less monitored can have illegal harvesting taking place. This illegal harvesting could include trees which are not of the harvestable level in Namibia and harvesting could be occurring without the proper permits from DoF. Even though they are able to resprout after fire, frost and herbivory (Kabajani 2016), Kabajani (2016) also noted that the distance to settlements had a large influence on the population structures of the species as trees closer to settlements are harvested first. This could mean that the trees that are left are not a good representation of the total population of the trees, and thus may have an influence on the development of the allometric models.

4.3.2 *Pterocarpus angolensis*

As with *B. africana*, there was not one model that reached the 30% uncertainty level in order to model above and below ground carbon storage. This could also be attributed to the lack of understanding of the root system for *P. angolensis*.

This is unfortunate, but when looking at only modelling above ground carbon storage the models did reach the level. Model number 6 was chosen as the most appropriate. This model includes more complicated measurements that would make it difficult for Namibian foresters to take these in the field with the proper accuracy needed. Expert and constant training would need to be done to ensure that the foresters and taking the correct measurements. The simpler the methods and measurements taken, the easier it will be to incorporate this into a Namibian forestry field data collection report (Ministry of Agriculture, Water and Forestry 2011). As with *B. africana*, trees could be destructively harvested in the non-destructive sites which will would provide actual biomass values for the areas of different LTAR. This could allow additional information to be brought into the models, which in turn could allow them to have less than 30% uncertainty. It would be possible to look at using model number 7, which only takes into account the dbh measurement of the tree. Using this model, you lose a 1% accuracy in the outcomes, but this would be easier for foresters to use in the field.

P. angolensis is considered the most valuable timber wood in the country (De Cauwer *et al.* 2016) and it would be highly valuable to have a model that would be able to estimate its carbon content. Since it is commonly cut down and used for timber (TRAFFIC 2015), it is important to know what carbon it is storing to help to understand the sustainability of this trade and how the carbon being released is affecting the surrounding woodlands (Geldenhuys 1997). Even though this tree has been explored and biomass tables developed by Chakanga *et al.* (1996), this is still not accurate enough to report on. It is worth nothing that only the above ground components of the tree are harvested and that is the only component lost to the environment. The below ground biomass is still intact. This could be an important consideration that should be put through to REDD+, to only be reporting on the above ground biomass rather than the total biomass.

4.4 Research Objective 3

Research objective number 3 looked at determining whether rainfall influences woody biomass for either tree species.

4.4.1 *Burkea africana*

For *B. africana*, a positive significant effect of rainfall on its mean biomass was reported. This was shown across the sites of Nkurenkuru to Katima Mulilo. This is significant because it provides further evidence (from objective one) that *B. africana* is a species which is affected by the amounts of rainfall. The mean biomass per tree in the Mashare site (lowest LTAR) was 0.846 tonnes while in Katima Mulilo (highest LTAR) was 3.825 tonnes. This shows an increase of 22.12% from the lowest to highest rainfall areas. This could also be linked into the amount of shrub cover in the areas. Daryanto *et al.* (2013) stated that shrub cover has increased in semi-arid regions worldwide, which was witnessed in the field. Although, this will not be an equal increase across all of the sites. This can be attributed to the large droughts that Namibia has had over the past two years, where the shrub cover has declined and fire frequencies have increased, which allowed *B. africana* to have more space to grow. This is an additional aspect of competition that could be added to the analysis to see these effects on biomass.

The harvestability of *B. africana* is also a possibility to consider. Since it is a much denser (Bjorkman 1999) than *P. angolensis,* and more difficult wood to work with, small trees are preferred when harvesting. This allows the larger trees to be able to grow undisturbed as more sophisticated machinery is needed, which is not always available in the communal areas especially in the thick sands. This could mean that more than one biomass model is needed for *B. africana*, possibly for communal areas versus protected areas.

4.4.2 *Pterocarpus angolensis*

For *P. angolensis*, rainfall doesn't show as clear of a link to the biomass as the biomass can be calculated for this tree without considering the rainfall element. There is a statistical difference between the sites, but only between the Mashare and Divundu sites. This is different for *B. africana*, where the rainfall is an important variable in these models. There was a significant difference in mean biomass across all sites. The issue is that the difference between most sites is not significant and do not follow a clear trend in the rainfall gradient. This could be due to many different attributes in Namibia, such as drought or the amount of fire in the area. Although, the high amount of selective harvesting (especially with close proximity to the road) may have had an effect on the data collected. Since the communities in these communal areas may not have access to sophisticated equipment, trees that are closer to the road tend to be harvested first. This was personally observed in many of the sites as the larger trees which were above the harvestable size of <45 cm in dbh as supported by Ministry of Environment and Tourism (1996) were found deeper in the forest. Still, 8 trees per diameter class were selected, so if there was selective harvesting, the only potential effect it could have had on our data would be that the straightest and longest branch free stems would have been harvested for poles or planks.

Although, according to Kabajani (2016), this species recorded no significant influences in relation to any of the environmental variables she measured. The species is noted to tolerate high fire temperatures while other species die off, this species is however protected from fire damage by a thick bark layer (Kabajani 2016). Potentially with an increase in rainfall there could be an increase in understory, and thus more fires and potentially hotter fires have occurred. Through this reasoning, more trees have been damaged in the higher rainfall area. It could be possible that the frequency and intensity of fires and the impact on the bark that could have a large influence growth behaviour of the trees. An issue is that once the bark is damaged, they become susceptible to fire (Kabajani 2016). This could link to the non-statistically different measures of bark thickness. Due to the human interactions, its fire tolerance has declined and therefore more trees are dying. This shows smaller trunk diameter because of fire damage at base of the trees and also shorter trees because they stop growing in length. This makes it difficult for field measurements, as some dbh classes are under-represented in the field.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

This study has proven that rainfall does statistically cause difference in some tree parameters for both *B. africana* and *P. angolensis*, concluding that the alternate hypothesis of the first research question can be accepted. For *B. africana*, all of the tree parameters measured showed a significant difference across the sites. For *P. angolensis*, all tree parameters except for the bark thickness at stump and dbh showed a significant difference across the sites. Therefore, it can be concluded that bark thickness measurements will not yield significant data results and are not needed for *P. angolensis* data collection. Across the rainfall gradient, it was shown that the parameters which had the lowest values were for the lowest LTAR sites. There are statistical differences between sites, but whether this is rainfall as the cause or something else has not been proven. It was also shown that the tree parameters for *B. africana* changed more than for *P. angolensis.*

The interaction between rainfall (sites) and species was also explored. Species on its own as well as rainfall (sites) were also considered as important variables to consider. It is noted that only bark thickness at stump and dbh reported a significant interaction effect on rainfall (sites) and species. This shows that the impact of site is not the same across the two species. For the other variables, rainfall had a similar effect, but the effect of the species had a large difference. This makes it very difficult to use an equation for all of the trees in Namibia. This indicates that for the different species, individual models need to be developed as different species differ statistically in their growth response at different sites. This will impact many of the forestry assessments across the regions as generalized measurements of the trees cannot be expanded beyond different rainfall regions.

Allometric models were created for both of the species. The interactions between the tree parameters has already shown that different models will be needed for each species of tree. For *B. africana*, no allometric models for total biomass fit within the 30% uncertainty levels. Unfortunately, this is not within the accepted percentage by REDD+ reporting countries. This means that the null hypothesis of objective 2 cannot be rejected for *B. africana* and individual non-destructive measurements of trees cannot credibly model total carbon levels (combined above and below ground). However, the above ground biomass could be modelled at the required level. Model number four would provide this and would entail taking measurements of crown diameter and stump diameter.

Similarly, for *P. angolensis,* none of the models which took into account total biomass fit within the 30% uncertainty levels. This means that the alternate hypothesis of objective 2 cannot be accepted for *P. angolensis*. Although, the above ground biomass could be modelled at the required level with model number six. This would involve taking measurements of dbh, height, bark thickness at dbh, crown diameter and stump diameter. With a sacrifice of only a percentage of accuracy for the model outcome, model number seven can be used with a simple dbh measurement.

For objective 3, an ANOVA test was done to see if rainfall influenced the biomass of either of the species across the rainfall gradient. Significant differences were shown for both, but rainfall could only describe a small amount of the variation between the sites. Also, only a few of the sites showed a significant difference from each other. Therefore, the null hypothesis of objective 3 is accepted as location does influence biomass, but the trend does not appear to be clearly linked to the clear rainfall gradient.

5.2 Recommendations

This study gives the results for the impact of a rainfall gradient on above and below ground carbon storage in the north-eastern region of Namibia, specifically for *B. africana* and *P. angolensis*. It was found that rainfall does not affect species in the same manner and additional data will need to be collected for the other woody species in order to assess the carbon storage over the whole area. It is likely that allometric models will need to be developed regionally in order to more accurately report on their carbon storage. For the best accuracy, both destructive and non-destructive measurements should be taken (as was done in this study).

Due to the high value of Namibia's dry woodland ecosystem, this information derived from this study can be used to decide whether or not the conversion of the woodlands to open rangeland or agricultural land is feasible. It has provided a baseline of data on the carbon storage of the two species studied which will enable the government to make more informed decisions regarding deforestation or debushing programmes planned. *B. africana* covers 2.8 m^2/hectare of the basal area while *P. angolensis* covers 3.9 m^2/hectare of the basal area (De Cauwer *et al.* 2016a). These two species are of high importance to Namibia and account for amount of the biomass in the woodlands of Namibia.

This information should also enable the government to guide the forest management activities being implemented and will allow them to promote more profitable harvesting of the trees in the regions. It will allow the forestry officials to to make informed decisions about the evaluation of land clearing for carbon credits as well as provide valuable information regarding the woodland health.

In addition, Namibia will now be able to provide more reliable information in accordance with their reporting obligations to UNFCCC and for the possibility to be get involved with the REDD+ programme and develop Namibia's implementation strategy. Carbon trading could become a large source of income for Namibia, but more information on other tree species will need to be completed in order to get a better idea on the woodland structures in these regions.

Data pertaining to the competition components in these woodlands can cause a great difference in the models selected. It is recommended for this data which was collected to see if it impacts the models developed. Wood density was also not included in this study, which has been shown to change across a rainfall gradient. This is another aspect which could be considered to allow the models to better fit. Also, below ground biomass (the root structures) needs additional analysis done as these are complicated structures that are not well understood enough in Namibia. It would be a possibility to use ground penetrating radar to get a better picture on the differences of the root structures. This could allow a better methodology to be defined in order to harvest the roots and more accurately measure the below ground biomass of the species.

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Appendices

Appendix 1 Field Sheet for Data Collection (non-destructive measurements)

Date: ____________________

Main Tree Data Measurements

Tree/Plot No:	**Site:**
GPS Coordinates	S
	E
Elevation	
Tree Species	
Phenology (Fr/Fl/L/N)	

Tree Height (m)	
DBH (cm)	
Bark Thickness at DBH (cm)	
Stump Diameter at 30 cm (cm)	
Bark Thickness at 30 cm (cm)	
Crown Diameter (cm) Ma A	
Crown Diameter (cm) Mi A	
Stem Height (m)	
Diameter at 2.3m (cm)	
Diameter at 3.3m (cm)	
Diameter at 4.3m (cm)	
Diameter at 5.3m (cm)	
Diameter at 6.3m (cm)	
Diameter at 7.3m (cm)	
Diameter at 8.3m (cm)	
Tree Cover	
% of Burkea Cover	
% of Kiaat Cover	
Soil Colour	
Soil Texture	
Bore collected (Y/N)	

DBH Class

5-15 cm	15-25 cm	25-35 cm	35-45 cm	<45 cm

Harvested Tree Data

Stand Diameter (cm)	
Height Harvested (m)	
Coppice (Y/N)	
Diameter of Coppice 1	
Diameter of Coppice 2	
Diameter of Coppice 3	
Diameter of Coppice 4	

Disturbance Data

Disturbance (Y/N)	
Type of Disturbance	
Damage class	

Shrub Cover (Shrub # to 10m)

N	
S	
E	
W	

Neighbour Data

Number of Neighbour and Species	**Direction from Main tree (deg)**	**Distance to Main Tree (cm)**	**DBH (cm)**	**Height (m)**	**Stump Diameter at 30 cm (cm)**	**Crown diameter (cm) Ma A**	**Crown diameter (cm) Mi A**
1:							
2:							
3:							
4:							
5:							

Notes

Appendix 2 Field Sheet for Data Collection (page 2 for destructive measurements)

Above Ground (tree) Measurements (Stem/Branch/Twig)

ID	Wet Weight

ID	Wet Disc W	Dry Disc W

Below Ground (root) Measurements (d=1-5cm, d=5-10cm, d-<10cm)

ID	Wet Weight	Depth Found

ID	Wet Root W	Dry Root W

Notes

Appendix 3 DoF Permit to Transport Samples from Mashare to Windhoek

PERMIT NUMBER 0152195

149 238 W

MINISTRY OF AGRICULTURE, WATER AND FORESTRY
Directorate of Forestry, Private Bag 13184, Windhoek

FOREST ACT, 2001 (ACT NO. 12 OF 2001)
FOREST PERMIT FOR TRANSPORTING
(Section 24, 27 and 33/ Regulation 12)

Transport Permit (Own use/~~Commercial~~	License/Permit No:

Permission is hereby granted in terms of the Forest Act, 2001 (Act 12 of 2001) as amended Forest Amendment Act No 13 of 2005 to

License Holder Name:	AMBER J. NOTT
Namibian ID/Passport / Birth Certificate No	01150010BG3G0001
Address:	P.O. BOX 35432 KLEIN KUPPE, WINDHOEK
Contact Telephone No:	0817532437
Name, Size, Farm No/ Village:	MASHARE AGRICULTURAL CAMP
District/Constituency	MASHARE
Region	KAVANGO EAST

To Transport Forest Produce specified below, subject to the conditions on the reverse side

SPECIES	PRODUCT	QUANTITY (m³, kg or ton, No of species)
P. angolensis	Wood discs	183 pieces
B. africana	Wood discs	183 pieces
Mix P. angolensis + B. africana	Root Samples	80 pieces

Loading Point Address	KAVANGO EAST (MASHARE)
Destination Address	WINDHOEK
Transport Agent/Vehicle Registration No	N 149 238 W

(FOR CONDITIONS SEE REVERSE SIDE)

This permit is valid from 29/09/2016 until 02/10/2016

AMOUNT PAID: N$ 10-00

RECEIPT NUMBER: 395064

OFFICIAL STAMP

MINISTRY OF AGRICULTURE WATER AND FORESTRY DIRECTORATE OF FORESTRY 29 SEP 2016 P/BAG 2144, RUNDU REPUBLIC OF NAMIBIA

No license/permit is valid without an official stamp

Name of Issuing officer: H. Seremia

Signature of Issuing officer: [signature]

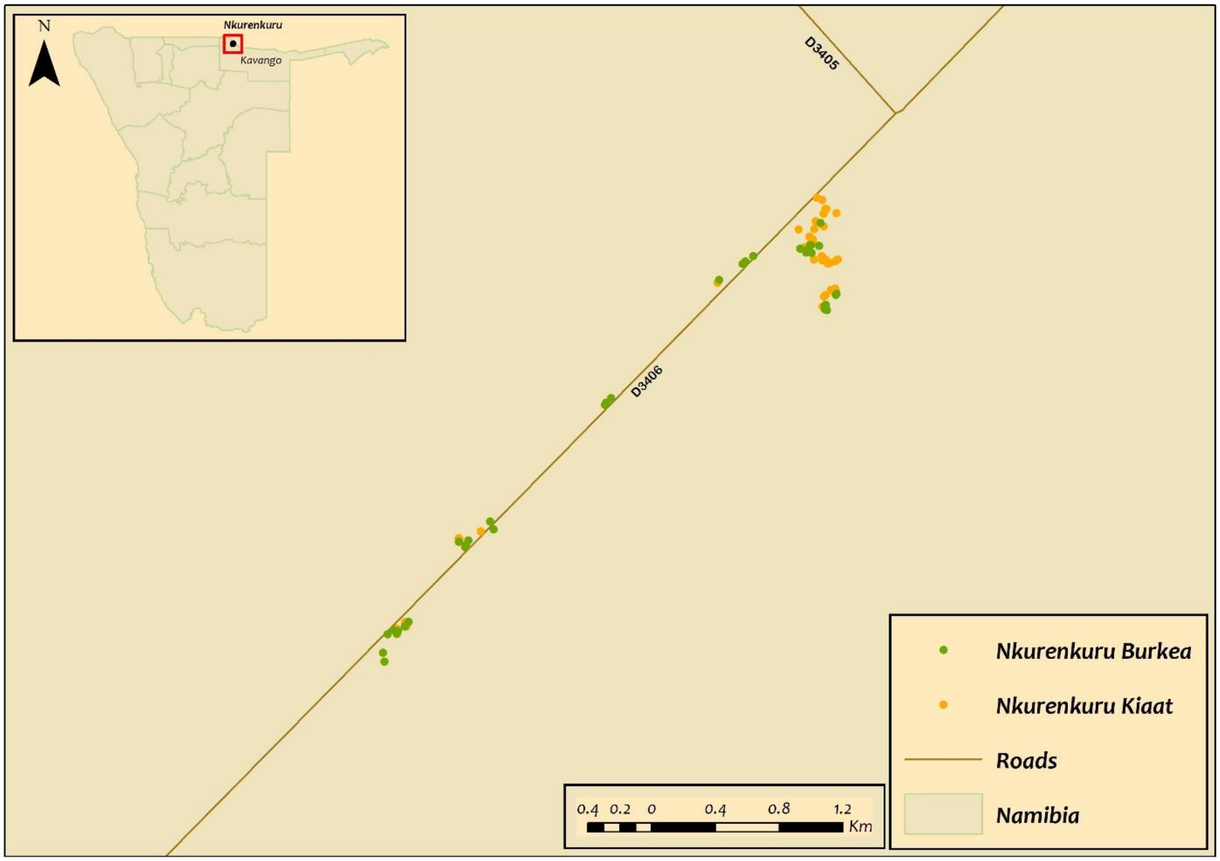
Place and Date: Rundu 29.09.16

Signature of Permit Holder: [signature]

MINISTRY OF AGRICULTURE, WATER AND FORESTRY DIRECTORATE OF FORESTRY MURURANI CHECK POINT, KAVANGO REGION 30 SEP 2016 P/BAG 2144 RUNDU REPUBLIC OF NAMIBIA

ALL OFFICIAL CORRESPONDENCE MUST BE ADDRESSED TO THE PERMANT SECRETARY

Appendix 4 GPS Points and Map for Nkurenkuru Site

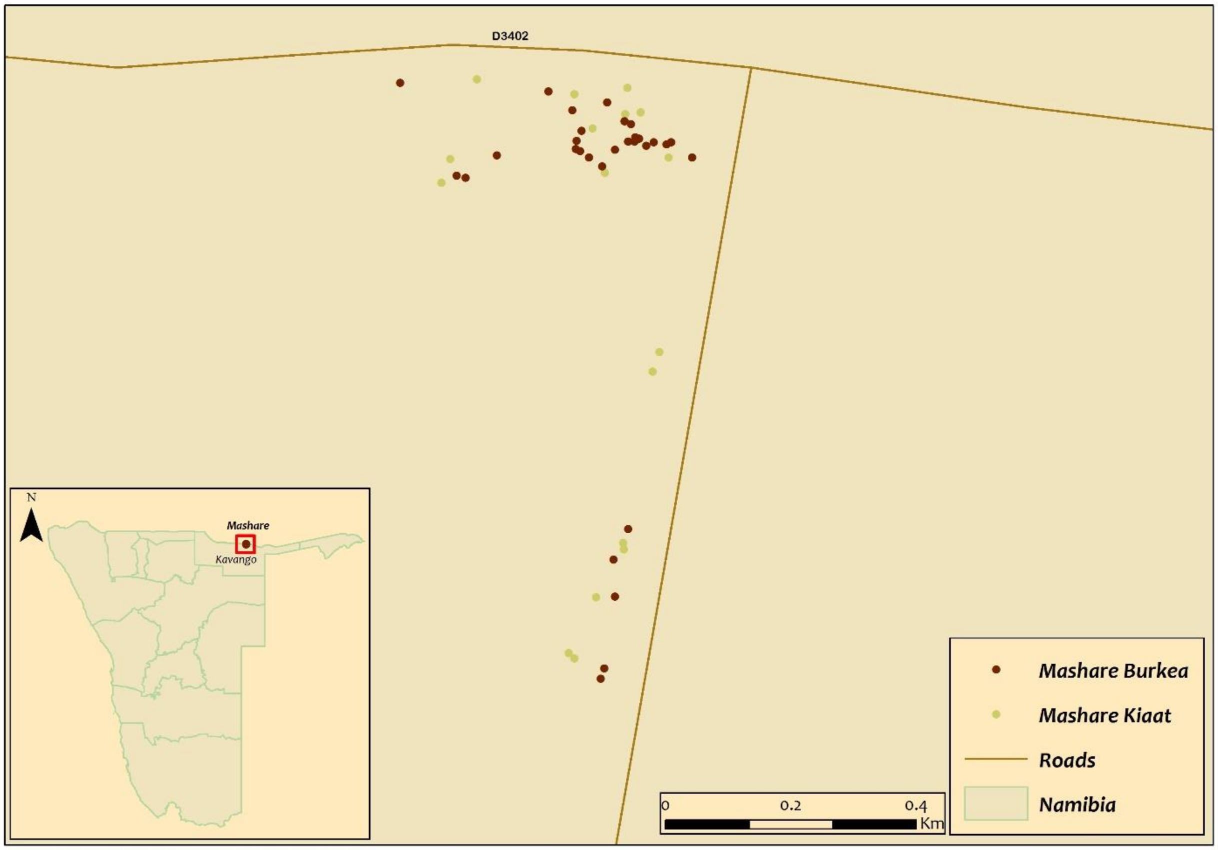


Tree/Plot No	DBH (cm)	GPS Co-Ordinates	
NK1	49.36	-17.64389	18.58924
NK2	47.13	-17.64377	18.58893
NK3	44.90	-17.64439	18.58942
NK4	28.98	-17.64440	18.58948
NK5	52.23	-17.64468	18.58932
NK6	9.55	-17.64464	18.59003
NK7	18.47	-17.64509	18.58888
NK8	45.54	-17.64537	18.58931
NK9	50.96	-17.64553	18.58880
NK10	56.05	-17.64595	18.58852
NK11	67.83	-17.64612	18.58871
NK12	47.77	-17.64624	18.58871
NK13	51.91	-17.64638	18.58863
NK14	47.77	-17.64638	18.58855
NK15	42.04	-17.64555	18.58790
NK16	41.40	-17.64726	18.58878

NK17	44.90	-17.64707	18.58922
NK18	44.59	-17.64725	18.58942
NK19	38.22	-17.64748	18.58955
NK20	44.90	-17.64731	18.58925
NK21	35.03	-17.64745	18.58969
NK22	26.75	-17.64724	18.59011
NK23	35.03	-17.64729	18.59006
NK24	32.48	-17.64735	18.58999
NK25	38.54	-17.64656	18.58825
NK26	34.71	-17.64896	18.58999
NK27	6.69	-17.64888	18.58995
NK28	10.19	-17.64888	18.58995
NK29	24.84	-17.64918	18.58997
NK30	34.55	-17.64896	18.58972
NK31	17.52	-17.64926	18.58941
NK32	9.55	-17.64935	18.58933
NK33	28.66	-17.64991	18.58925
NK34	18.47	-17.64857	18.58334
NK35	15.29	-17.66260	18.56997
NK36	5.41	-17.66339	18.56915
NK37	23.89	-17.66302	18.56877
NK38	11.46	-17.66297	18.56873
NK39	23.57	-17.66777	18.56576
NK40	22.93	-17.66771	18.56569
NK41	11.15	-17.66796	18.56578
NK42	11.78	-17.66807	18.56523
NB1	48.09	-17.64520	18.58913
NB2	13.38	-17.64644	18.58859
NB3	11.78	-17.64644	18.58856
NB4	9.87	-17.64644	18.58856
NB5	50.96	-17.64647	18.58905
NB6	48.09	-17.64687	18.58864
NB7	44.59	-17.64669	18.58845
NB8	51.27	-17.64663	18.58798
NB9	45.86	-17.64669	19.58842
NB10	13.06	-17.64686	18.58834
NB11	10.19	-17.64686	18.58834
NB12	8.28	-17.64919	18.59003
NB13	9.55	-17.64925	18.58999
NB14	11.46	-17.64980	18.58944
NB15	15.29	-17.64980	18.58944

NB16	7.32	-17.64986	18.58937
NB17	34.39	-17.65011	18.58950
NB18	28.98	-17.65006	18.58937
NB19	30.57	-17.64706	18.58535
NB20	63.06	-17.64736	18.58489
NB21	38.54	-17.64750	18.58473
NB22	43.31	-17.64840	18.58342
NB23	43.63	-17.65507	18.57732
NB24	33.76	-17.65533	18.57704
NB25	49.68	-17.65544	18.57697
NB26	34.39	-17.66310	18.56927
NB27	54.78	-17.66336	18.56913
NB28	43.63	-17.66347	18.56908
NB29	35.67	-17.66318	18.56873
NB30	30.57	-17.66248	18.57068
NB31	35.99	-17.66204	18.57048
NB32	39.49	-17.66769	18.56590
NB33	19.75	-17.66796	18.56568
NB34	32.80	-17.66821	18.56529
NB35	34.08	-17.66822	18.56521
NB36	15.29	-17.66837	18.56523
NB37	18.79	-17.66815	18.56503
NB38	18.15	-17.66839	18.56471
NB39	20.70	-17.66944	18.56445
NB40	20.38	-17.66994	18.56453

Appendix 5 GPS Points and Map for Mashare Site

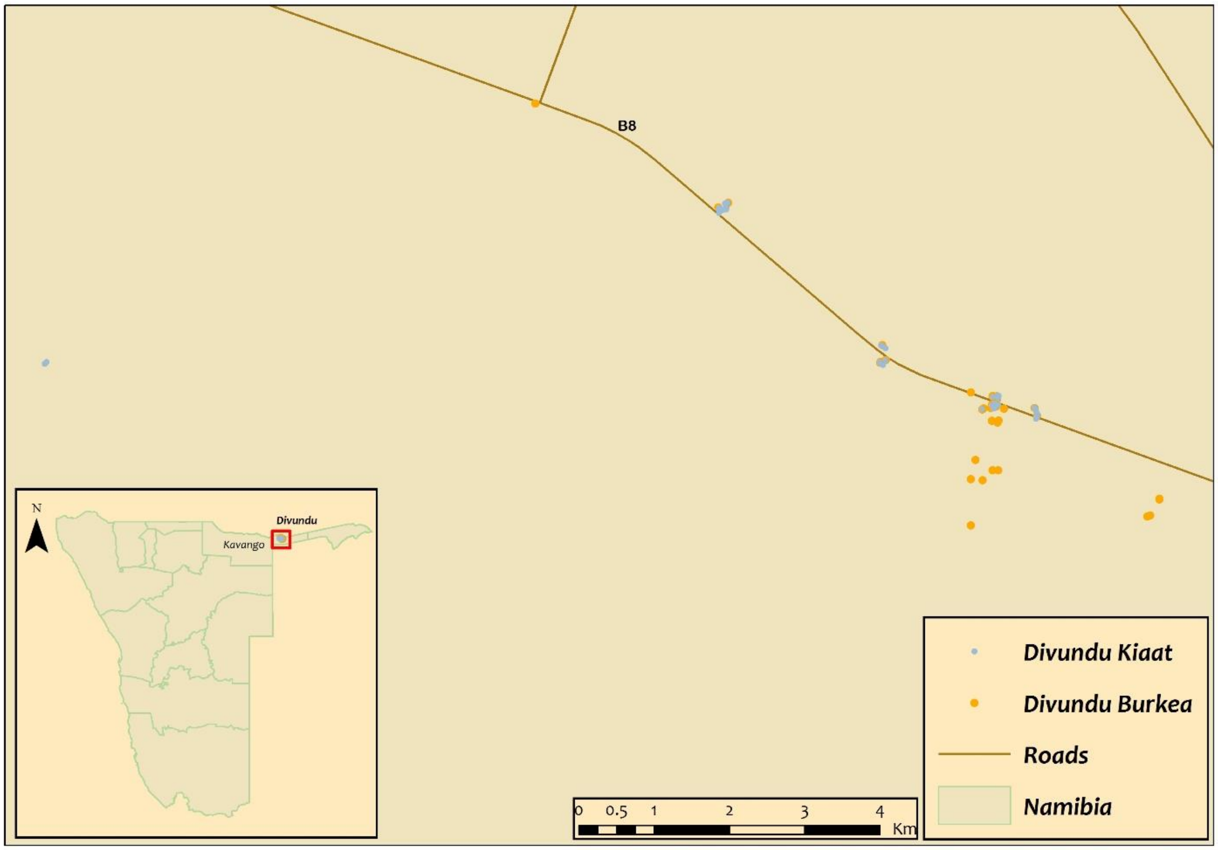


Tree/Plot No	DBH (cm)	GPS Co-Ordinates	
MK1	40.76	-17.90032	20.20159
MK2	39.81	-17.90035	20.20137
MK3	25.16	-17.90075	20.20203
MK4	32.48	-17.89997	20.20140
MK5	35.35	-17.89997	20.20140
MK6	7.32	-17.90376	20.20186
MK7	5.10	-17.90650	20.20134
MK8	26.43	-17.90035	20.20137
MK9	33.76	-17.90080	20.20167
MK10	35.03	-17.90078	20.20196
MK11	20.38	-17.90080	20.20167
MK12	21.97	-17.90074	20.20141
MK13	36.31	-17.90078	20.20196
MK14	30.25	-17.90119	20.20108
MK15	35.67	-17.90075	20.20203
MK16	26.75	-17.90075	20.20203

MK17	19.75	-17.90075	20.20203
MK18	17.20	-17.90075	20.20203
MK19	8.60	-17.90404	20.20176
MK20	8.60	-17.90404	20.20176
MK21	9.55	-17.90659	20.20135
MK22	5.41	-17.90728	20.20095
MK23	5.10	-17.90808	20.20056
MK24	5.41	-17.90816	20.20064
MK25	23.25	-17.89997	20.20140
MK26	28.66	-17.90018	20.20111
MK27	28.66	-17.90018	20.20111
MK28	8.60	-17.90018	20.20111
MK29	23.57	-17.90006	20.20064
MK30	20.70	-17.90006	20.20064
MK31	21.02	-17.90055	20.20090
MK32	23.57	-17.90002	20.20027
MK33	21.34	-17.90073	20.20067
MK34	30.89	-17.90073	20.20067
MK35	16.56	-17.90085	20.20066
MK36	18.79	-17.90097	20.20199
MK37	15.29	-19.90133	20.19873
MK38	15.61	-17.90099	20.19886
MK39	17.52	-17.90123	20.19895
MK40	15.45	-17.89985	20.19924
MB1	20.38	-17.90075	20.20203
MB2	22.29	-17.90018	20.20111
MB3	7.01	-17.90097	20.20233
MB4	6.05	-17.90097	20.20233
MB5	25.16	-17.90045	20.20136
MB6	30.25	-17.90045	20.20136
MB7	18.47	-17.90049	20.20145
MB8	24.52	-17.90068	20.20151
MB9	20.70	-17.90070	20.20157
MB10	29.94	-17.90075	20.20178
MB11	21.02	-17.90078	20.20196
MB12	11.15	-17.90080	20.20167
MB13	25.48	-17.90074	20.20141
MB14	28.03	-17.90074	20.20141
MB15	30.25	-17.90074	20.20150
MB16	25.16	-17.90078	20.20196
MB17	19.11	-17.90074	20.20141

MB18	23.57	-17.90086	20.20122
MB19	20.38	-17.90110	20.20104
MB20	11.15	-17.90075	20.20203
MB21	15.92	-17.90075	20.20203
MB22	19.75	-17.90075	20.20203
MB23	5.41	-17.90674	20.20120
MB24	6.37	-17.90830	20.20107
MB25	7.64	-17.90845	20.20102
MB26	5.10	-17.90727	20.20122
MB27	5.10	-17.90630	20.20141
MB28	16.88	-17.90029	20.20061
MB29	15.13	-17.90002	20.20027
MB30	19.75	-17.90002	20.20027
MB31	19.75	-17.90059	20.20074
MB32	21.34	-17.90073	20.20067
MB33	21.66	-17.90085	20.20066
MB34	30.89	-17.90088	20.20072
MB35	23.89	-17.90097	20.20085
MB36	22.93	-17.90097	20.20085
MB37	15.29	-17.90094	20.19953
MB38	18.79	-17.90126	20.19908
MB39	17.52	-17.90123	20.19895
MB40	15.92	-17.89990	20.19814

Appendix 6 GPS Points and Map for Divundu Site

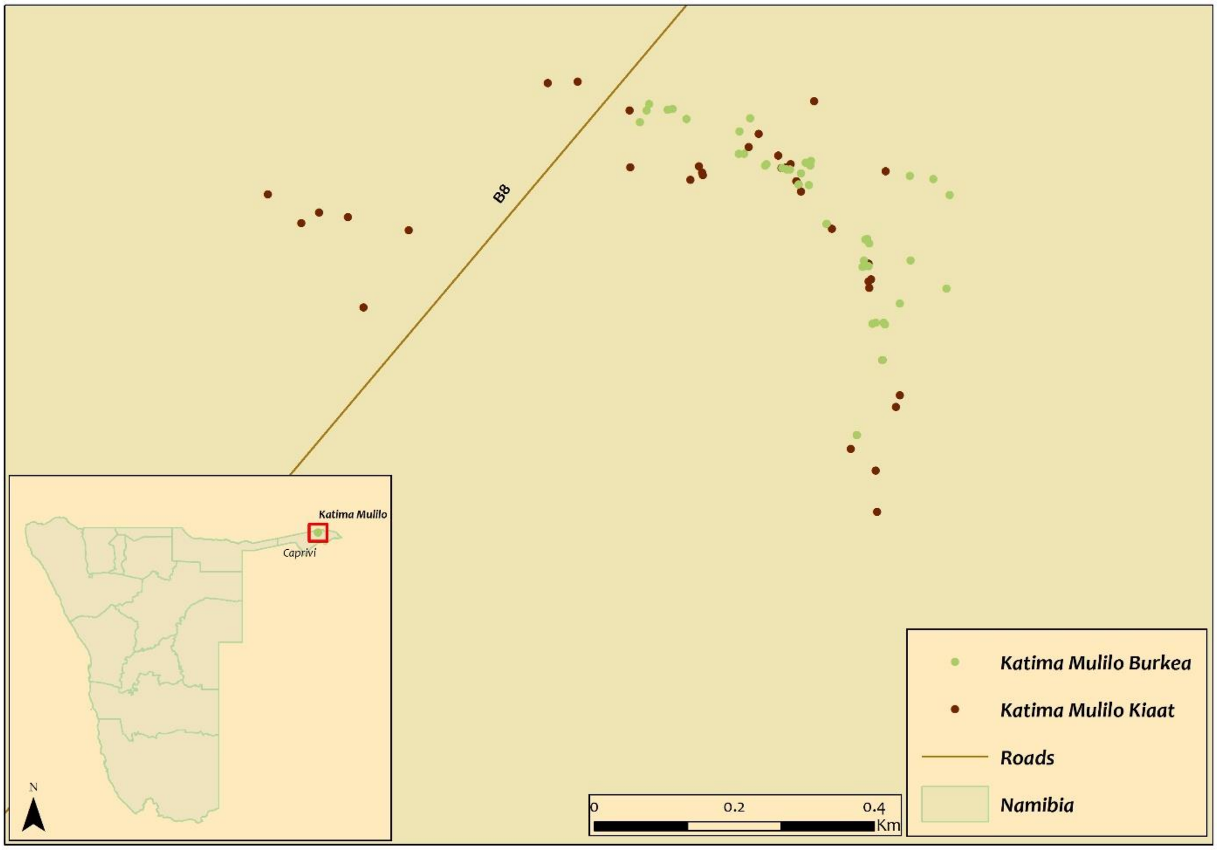


Tree/Plot No	DBH (cm)	GPS Co-Ordinates	
DK1	55.41	-18.05254	21.37031
DK2	62.10	-18.05222	21.37069
DK3	57.64	-18.05217	21.37031
DK4	50.96	-18.05189	21.37038
DK5	59.24	-18.05211	21.37119
DK6	41.08	-18.05186	21.37117
DK7	47.45	-18.05189	21.37120
DK8	40.13	-18.05141	21.37106
DK9	30.25	-18.05135	21.37119
DK10	34.39	-18.05132	21.37139
DK11	18.47	-18.07013	21.39028
DK12	9.55	-18.07035	21.28997
DK13	30.89	-18.07070	21.38991
DK14	21.02	-18.07055	21.28977
DK15	38.85	-18.07047	21.38957
DK16	36.31	-18.07035	21.38956

DK17	33.12	-18.06842	21.38978
DK18	36.94	-18.06870	21.39022
DK19	14.01	-18.06837	21.38972
DK20	7.01	-18.07549	21.40300
DK21	6.05	-18.07552	21.40299
DK22	5.10	-18.07553	21.40303
DK23	5.10	-18.07569	21.40332
DK24	28.34	-18.07581	21.40329
DK25	30.57	-18.07586	21.40328
DK26	18.79	-18.07590	21.40314
DK27	22.61	-18.07597	21.40180
DK28	29.30	-18.07445	21.40372
DK29	29.62	-18.07544	21.40372
DK30	56.05	-18.07438	21.40373
DK31	18.79	-18.07436	21.40368
DK32	43.31	-18.07461	21.40370
DK33	5.10	-18.07451	21.40306
DK34	10.83	-18.07595	21.40811
DK35	15.61	-18.07582	21.40803
DK36	20.06	-18.07619	21.40822
DK37	24.52	-18.07655	21.40839
DK38	44.90	-18.07683	21.40836
DK39	41.08	-18.07713	21.40821
DK40	65.29	-18.07533	21.40332
DB1	7.01	-18.05132	21.37145
DB2	39.49	-18.05188	21.37023
DB3	32.17	-18.07010	21.39025
DB4	24.20	-18.07044	21.38959
DB5	28.34	-18.07030	21.38961
DB6	11.46	-18.06832	21.38984
DB7	18.15	-18.07547	21.40294
DB8	10.83	-18.07557	21.40304
DB9	20.38	-18.07571	21.40329
DB10	20.38	-18.07569	21.40340
DB11	41.08	-18.07586	21.40279
DB12	38.85	-18.07589	21.40196
DB13	31.21	-18.07600	21.40178
DB14	10.51	-18.07501	21.40349
DB15	17.52	-18.07482	21.40355
DB16	23.57	-18.07459	21.40351
DB17	35.99	-18.07467	21.40326

DB18	23.89	-18.07446	21.40352
DB19	24.52	-18.07449	21.40303
DB20	25.16	-18.07441	21.40307
DB21	7.32	-18.07586	21.40803
DB22	9.87	-18.07676	21.40832
DB23	11.78	-18.07546	21.40328
DB24	14.01	-18.07592	21.40439
DB25	33.44	-18.07731	21.40375
DB26	26.43	-18.07759	21.40362
DB27	35.35	-18.07736	21.40292
DB28	28.34	-18.08327	21.40370
DB29	28.34	-18.08327	21.40303
DB30	46.18	-18.08448	21.40184
DB31	35.35	-18.08435	21.40042
DB32	43.31	-18.08207	21.40100
DB33	35.35	-18.08987	21.40042
DB34	40.13	-18.03943	21.34837
DB35	41.40	-18.07399	21.40041
DB36	32.48	-18.08870	21.42187
DB37	35.35	-18.08881	21.42150
DB38	31.85	-18.08670	21.42294
DB39	39.81	-18.08679	21.42294
DB40	38.22	-18.09317	21.41706

Appendix 7 GPS Points and Map for Katima Mulilo Site



Tree/Plot No	DBH (cm)	GPS Co-Ordinates	
KMK1	36.62	-17.58297	24.23394
KMK2	33.76	-17.58369	24.23483
KMK3	35.35	-17.58377	24.23487
KMK4	5.10	-17.58380	24.23488
KMK5	26.43	-17.58386	24.23472
KMK6	59.87	-17.58355	24.23585
KMK7	32.80	-17.58370	24.23595
KMK8	5.41	-17.58370	24.23395
KMK9	11.78	-17.58366	24.23601
KMK10	15.29	-17.58371	24.23589
KMK11	71.66	-17.58388	24.23608
KMK12	35.03	-17.58388	24.23608
KMK13	6.69	-17.58392	24.23611
KMK14	10.19	-17.58401	24.23614
KMK15	47.13	-17.58443	24.23647
KMK16	6.37	-17.58449	24.23654

KMK17	5.10	-17.58327	24.23560
KMK18	28.98	-17.58344	24.23547
KMK19	29.62	-17.58494	24.23701
KMK20	15.61	-17.58517	24.23701
KMK21	9.55	-17.58514	24.23704
KMK22	15.61	-17.58525	24.23702
KMK23	20.06	-17.58618	24.23719
KMK24	15.61	-17.58618	24.23719
KMK25	15.29	-17.58663	24.23741
KMK26	15.92	-17.58678	24.23736
KMK27	18.47	-17.58714	24.23686
KMK28	33.44	-17.58732	24.23678
KMK29	34.08	-17.58760	24.23710
KMK30	30.57	-17.58813	24.23712
KMK31	73.25	-17.58285	24.23631
KMK32	92.36	-17.58378	24.23723
KMK33	57.01	-17.58262	24.23289
KMK34	39.17	-17.58260	24.23327
KMK35	41.40	-17.58451	24.23110
KMK36	36.31	-17.58428	24.22995
KMK37	37.26	-17.58442	24.22972
KMK38	51.91	-17.58434	24.23032
KMK39	35.67	-17.58405	24.22929
KMK40	50.32	-17.58550	24.23052
KMB1	53.82	-17.58289	24.23419
KMB2	8.28	-17.58297	24.23416
KMB3	33.76	-17.58312	24.23407
KMB4	32.48	-17.58296	24.23443
KMB5	51.59	-17.58308	24.23467
KMB6	37.26	-17.58295	24.23449
KMB7	43.63	-17.58373	24.23596
KMB8	35.03	-17.58373	24.23600
KMB9	51.91	-17.58364	24.23620
KMB10	48.09	-17.58368	24.23626
KMB11	7.64	-17.58362	24.23627
KMB12	22.93	-17.58378	24.23614
KMB13	31.85	-17.58392	24.23611
KMB14	39.17	-17.58393	24.23624
KMB15	26.75	-17.58443	24.23647
KMB16	9.24	-17.58406	24.23805
KMB17	29.62	-17.58353	24.23541

KMB18	43.31	-17.58353	24.23534
KMB19	40.45	-17.58463	24.23697
KMB20	8.92	-17.58462	24.23699
KMB21	31.53	-17.58468	24.23702
KMB22	47.13	-17.58490	24.23695
KMB23	28.03	-17.58497	24.23701
KMB24	5.73	-17.58498	24.23693
KMB25	24.52	-17.58570	24.23710
KMB26	24.84	-17.58571	24.23706
KMB27	11.15	-17.58572	24.23722
KMB28	7.64	-17.58570	24.23720
KMB29	16.88	-17.58618	24.23719
KMB30	13.69	-17.58324	24.23535
KMB31	50.96	-17.58366	24.23570
KMB32	43.95	-17.58371	24.23590
KMB33	28.34	-17.58368	24.23568
KMB34	35.03	-17.58714	24.23686
KMB35	53.82	-17.58307	24.23549
KMB36	21.66	-17.58381	24.23754
KMB37	21.34	-17.58385	24.23784
KMB38	23.57	-17.58490	24.23755
KMB39	24.20	-17.58545	24.23741
KMB40	55.73	-17.58526	24.23801

Appendix 8 Model Coefficients for the Assessment of the Total Biomass Allometric Models Developed from the Destructive Harvesting Sampling Conducted in Mashare for *Burkea africana* and *Pterocarpus angolensis*

Model #	Form
1	$Log(biomass) = \beta_0 + \beta_1 Log(D^2H) + \varepsilon$
2	$Log(biomass) = \beta_0 + \beta_1 Log(DBH) + \beta_2 log(H) + \varepsilon$
3	$Log(biomass) = \beta_0 + \beta_1 Log(D^2H) + \beta_2$ log (Bark thickness) + β_3 log (Crown diameter) + β_4 log (stump diameter) + ε
4	$Log(biomass) = \beta_0 + \beta_1$ log (Bark thickness) + β_2 log (Crown diameter) + β_3 log (stump diameter) + ε
5	$Log(biomass) = \beta_0 + \beta_1$ log (Crown diameter) + β_2 log (stump diameter) + ε
6	$Log(biomass) = \beta_0 + \beta_1 Log(D^2H) + \beta_2 log(DBH) + \beta_3$ log (Bark thickness) + β_4 log (Crown diameter) + β_5 log (stump diameter) + ε
7	$Log(biomass) = \beta_0 + \beta_1 Log(DBH) + \varepsilon$

Total Biomass	Model Number	β_0	β_1	β_2	β_3	β_4	β_5
Burkea africana	1	6.004	0.218				
	2	6.060	0.667	-0.172			
	3	7.225	0.012	0.656	-0.454	1.044	
	4	7.206	0.657	-0.045	1.074		
	5	7.025	-0.042	1.093			
	6	8.089	0.866	-2.224	0.734	-0.077	1.386
	7	6.024	0.569				
Pterocarpus angolensis	1	5.065	0.291				
	2	5.106	0.797	-0.050			
	3	3.337	-0.146	0.151	0.457	0.696	
	4	3.723	0.114	0.366	0.394		
	5	3.676	0.356	0.447			
	6	3.375	-0.338	0.647	0.150	0.484	0.497
	7	5.096	0.767				

Appendix 9 Model Coefficients for the Assessment of the Above Ground Biomass Allometric Models Developed from the Destructive Harvesting Sampling Conducted in Mashare for *Burkea africana* and *Pterocarpus angolensis*

Model #	Form
1	Log(biomass) = $\beta_0 + \beta_1$ Log (D^2H) + ε
2	Log(biomass) = $\beta_0 + \beta_1$ Log(DBH) + β_2 log(H) + ε
3	Log(biomass) = $\beta_0 + \beta_1$ Log (D^2H) + β_2 log (Bark thickness) + β_3 log (Crown diameter) + β_4 log (stump diameter) + ε
4	Log(biomass) = $\beta_0 + \beta_1$ log (Bark thickness) + β_2 log (Crown diameter) + β_3 log (stump diameter) + ε
5	Log(biomass) = $\beta_0 + \beta_1$ log (Crown diameter) + β_2 log (stump diameter) + ε
6	Log(biomass) = $\beta_0 + \beta_1$ Log (D^2H) + β_2 log (DBH) + β_3 log (Bark thickness) + β_4 log (Crown diameter) + β_5 log (stump diameter) + ε
7	Log(biomass) = $\beta_0 + \beta_1$ Log (DBH) + ε

Above Ground Biomass	Model Number	β_0	β_1	β_2	β_3	β_4	β_5
Burkea africana	1	-0.824	0.950				
	2	-0.070	2.428	0.066			
	3	-2.596	-0.072	-0.423	0.123	2.923	
	4	-2.476	-0.426	0.106	2.739		
	5	-2.359	0.083	2.727			
	6	-4.176	-1.634	4.065	-0.566	0.697	2.299
	7	-0.684	2.466				
Pterocarpus angolensis	1	-0.425	0.847				
	2	-0.343	2.132	0.147			
	3	-2.246	-0.042	1.018	0.451	1.771	
	4	-2.135	1.008	0.425	1.684		
	5	-2.544	0.341	2.143			
	6	-2.260	0.025	-0.225	1.018	0.441	1.840
	7	-0.315	2.221				

Appendix 10 Model Coefficients for the Assessment of the Below Ground Biomass Allometric Models Developed from the Destructive Harvesting Sampling Conducted in Mashare for *Burkea africana* and *Pterocarpus angolensis*

Model #	**Form**
1	Log(biomass) = $\beta_0 + \beta_1$ Log (D^2H) + ε
2	Log(biomass) = $\beta_0 + \beta_1$ Log(DBH) + β_2 log(H) + ε
3	Log(biomass) = $\beta_0 + \beta_1$ Log (D^2H) + β_2 log (Bark thickness) + β_3 log (Crown diameter) + β_4 log (stump diameter) + ε
4	Log(biomass) = $\beta_0 + \beta_1$ log (Bark thickness) + β_2 log (Crown diameter) + β_3 log (stump diameter) + ε
5	Log(biomass) = $\beta_0 + \beta_1$ log (Crown diameter) + β_2 log (stump diameter) + ε
6	Log(biomass) = $\beta_0 + \beta_1$ Log (D^2H) + β_2 log (DBH) + β_3 log (Bark thickness) + β_4 log (Crown diameter) + β_5 log (stump diameter) + ε
7	Log(biomass) = $\beta_0 + \beta_1$ Log (DBH) + ε

Below Ground Biomass	Model Number	β_0	β_1	β_2	β_3	β_4	β_5
Burkea africana	1	6.885	0.0275				
	2	6.880	0.0328	0.065			
	3	8.107	-0.037	0.776	-0.391	0.547	
	4	8.169	0.775	-0.400	0.451		
	5	7.956	-0.358	0.474			
	6	9.161	1.450	-3.871	0.912	-0.938	1.142
	7	6.893	0.070				
Pterocarpus angolensis	1	6.284	0.037				
	2	6.219	-0.272	0.589			
	3	4.362	-0.001	-0.264	0.660	-0.636	
	4	4.364	-0.264	0.659	-0.637		
	5	4.471	0.681	-0.758			
	6	4.346	0.079	-0.268	0.264	0.648	0.553
	7	6.329	0.083				