Natural Regeneration Potential of *Pterocarpus angolensis* (Kiaat Tree) in the dry forests of northern Namibia.

By

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Declaration

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Abstract

Pterocarpus angolensis is one of the timber tree species that regenerates naturally in the dry forest of Namibia, mainly assisted by the influence of forest fires. Tree development goes through a prolonged suffrutex stage to reach the sapling stage and then, finally, the bole tree stage. This study focused on assessing the main factors facilitating the development of *Pterocarpus angolensis* seedlings through the suffrutex stage to the sapling stage in Namibia dry forests. To achieve the study objectives three study locations (Okongo and Ncumcara Community Forests and Caprivi State Forest) were selected, representing a rainfall gradient. Within each study location, two different fire history treatments (recently burnt (RB) and recently unburnt (RU)) were selected, and four plots were randomly selected from each fire history treatment.

Face to face individual interviews was conducted with community members surrounding the three forests to obtain indigenous knowledge information about *Pterocarpus angolensis* tree development. Seedlings and saplings found in all plots were counted and measured (tree height and diameter at breast height (DBH)) while trees more than 3 m high were only counted and measured for DBH. Laboratory analysis was performed to determine basic soil texture and nutrient status. In addition, destructive sampling was done on individual trees in the seedling and sapling stages at each study location. The destructive samples allowed for estimation of biomass in above and below ground components, determination of carbohydrate storage in the taproots and estimation of tree age by counting growth rings on the neck disc of the taproot sample. These measures could shed light on the tree development through the suffrutex stage.

The main agents causing *Pterocarpus angolensis* tree damage and stand disturbances observed are drought, fires, insects, diseases, temperature, lightning, wind, animals and humans. Forest fires were found to be one of the major disturbances in all the study locations, particularly damaging to seedlings when fire intensity is high. Likewise, the most important factors influencing the tree development from seedlings to sapling and sapling to bole tree stages are soil water, soil fertility, plant competition, sunlight and fires. Through counting growth rings of taproot neck discs, it is estimated that the ages of seedlings most commonly range from 5 to 12 years in the dry forests of Okongo, Ncumcara and Caprivi.

The soil texture in the three forests is dominated by sand, with the soil reaction usually being moderately acidic while the soils have low levels of organic carbon, phosphorus and exchangeable base cations.

This study revealed that Caprivi State Forest (location with the highest rainfall) has the highest stand density followed by Okongo Community Forest and Ncumcara Community Forest with the lowest. Trees were grouped into different DBH and height classes. The highest numbers of trees are found in DBH class 0 – 10 cm and in height class 0.6 – 1.0 m at Okongo Community Forest but at Ncumcara and Caprivi many of the trees are in height class 1.1 – 1.5 m. The mean DBH difference is significant between locations but not significant between fire history treatments. A higher abundance of mature trees are found at Okongo Community Forest while a greater abundance of saplings occur at Ncumcara Community Forest which shows a significant difference between study locations. Seedling abundance is the same across study locations and fire history treatments. The difference in stand structure between study locations appears to be strongly influenced by different management regimes on the three locations.

A majority of respondents from all the study locations alleged soil water followed by soil fertility as the main influential factors to *Pterocarpus angolensis* development. Again, most of the respondents revealed that seedling takes 4 – 7 years to reach sapling stage and their main environmental disturbance is fire. Tree cutting by members of the community was also perceived by the respondents as an important non-environmental disturbance. The most abundant tree development stage perceived by respondents was mature trees while seedlings rated the sparsest stage. Based on the respondents no silvicultural practices are performed to promote *Pterocarpus angolensis* growth. It follows that the Kiaat trees are currently growing without human intervention that might enhance their development. A combination of social survey (interview) and ecological survey provided reliable information on ecological processes.

A weak positive significant correlation relationship existed between shoot mass (aboveground biomass) and taproot mass (belowground biomass), meaning when the taproot mass increases the shoot mass also increases. Analysis of non-structural carbohydrates (NSC) storage in taproots showed that both sugar and starch contents in the taproots could facilitate the survival of the tree during suffrutex stages and its rapid growth thereafter.

Based on this study *Pterocarpus angolensis* regeneration in these three dry forests is poor because seedling abundance is the lowest compared to saplings and mature trees. These study findings can be used as the basis for further studies to predict *Pterocarpus angolensis* natural regeneration in the dry forests, as well as input when management regimes are being developed for the dry forests of North Namibia.

Opsomming

Pterocarpus angolensis (Kiaat) is een van die boomspesies wat natuurlik verjong in die droë bosveld van Namibië, met die hulp van bosbrande. Die boom ontwikkel deur ŉ lang semi-struik stadium waartydens die boompies as saailinge bekendstaan. Daarna ontwikkel dit deur die *jongboom* stadium tot dit uiteindelik die kroon stadium bereik. Hierdie studie fokus op die faktore bydra tot die ontwikkeling van *Pterocarpus angolensis* van die semi-struik stadium na die *jongboom* stadium in die droë bosveld van Namibië. Om die doelstellings van die tesis te bereik is drie studiegebiede gekies langs ŉ reënvalgradiënt (naamlik Okongo en Ncumcara gemeenskapsbosse asook Caprivi Staatsbos). Binne elke studiegebied is twee behandelings met verskillende brandgeskiedenis gekies (gebrand of nie-gebrand in die onlangse verlede). Vier persele is ewekansig uit elk van hierdie behandelings gekies vir eksperimentering.

Persoonlike onderhoude is gevoer met gemeenskapslede wat in die omgewing woon ten einde inheemse kennis en inligting te versamel oor die ontwikkeling van die jong *Pterocarpus angolensis* bome. Alle saailinge en *jongbome* wat voorkom in die persele is getel en gemeet (boomhoogte en deursnee op borshoogte (DBH)) terwyl bome wat hoër as 3 m is, slegs getel en vir DBH gemeet is. Laboratoriumtoetse is gedoen op grondmonsters ten einde ‘n basiese beskrywing van die grondtekstuur en voedingstofstatus te verkry. Verder is destruktiewe bemonstering toegepas op bome in beide die saailing en *jongboom* stadium op elke studiegebied. Hierdie bemonstering het dit moontlik gemaak om bogrondse en ondergrondse biomassa te skat, om die opberging van koolhidrate in die penwortels te bepaal, en ook om die boom ouderdom te skat vanaf jaarringe in die nek van die penwortel monster. Hierdie metings kon lig werp op die boomontwikkeling deur die semi-struik stadium.

Die faktore wat skade aan *Pterocarpus angolensis* bome veroorsaak asook versteuring van die opstande waarin die bome voorkom is droogte, brande, insekte, siektes, temperatuur uiterstes, weerlig, wind, diere en mense. Die bevindinge dui op bosbrande as een van die belangrikste versteuringsfaktor in al drie studiegebiede; dit is veral skadelik vir saailinge in die semi-struik stadium wanneer die vuurintensiteit hoog is. Die faktore wat die boomontwikkeling van saailing, na *jongboom* en kroonstadium beïnvloed is hoofsaaklik grondwater, grondvrugbaarheid, plantkompetisie, sonlig en brande. Die ouderdom van saailinge (bepaal vanaf jaarring tellings in die nek van penwortel monsters) van die meeste saailinge én

jongbome is na raming tussen 5 en 12 jaar vir die droë bosse in die studiegebiede van Okongo, Ncumcara en Caprivi. Die grondtekstuur van hierdie studie se drie bosgebiede is hoofsaaklik sanderig, met ’n effens suur grondreaksie terwyl die gronde lae vlakke van organiese koolstof, fosfor, en uitruilbare basiese katione bevat.

Die studie het aangedui dat Caprivi staatsbos (met die hoogste reënval) die digste opstande huisves, gevolg deur Okongo en dan Ncumcara gemeenskapsbos, met die laagste digtheid. Bome is gegroepeer in verskillende DBH en hoogte klasse. Die meeste bome kom voor in die DBH klas van 0-10 cm en in die hoogteklas van 0.6 – 1.0 m by Okongo, maar by Ncumcara en Caprivi is daar meer bome in die hoogteklas van 1.1 - 1.5 m. Die gemiddelde DBH verskil is betekenisvol tussen studiegebiede, maar is nie betekenisvol verskillend tussen brandgeskiedenis behandelings nie. ’n Hoër voorkoms van volwasse bome is by Okongo aangetref, terwyl ’n hoër voorkoms van *jongbome* by Ncumcara waargeneem is, en hierdie verskil was statisties betekenisvol. Die voorkoms van saailinge is soortgelyk oor alle studiegebiede en brandgeskiedenis behandelings heen. Die verskil in die struktuur van die opstande op die drie studiegebiede word skynbaar sterk beïnvloed deur verskillende bestuurspraktyke wat in elke gebied toegepas word.

Die meerderheid van respondente van al drie studiegebiede beweer dat grondwater, gevolg deur grondvrugbaarheid die belangrikste faktore is wat *P. angolensis* ontwikkeling beïnvloed. Meeste van die respondente onthul dat saailinge 4 tot 7 jaar neem om die *jongboom* stadium te bereik en dat die belangrikste versteuringsagent bosbrande is. ’n Belangrike nie-omgewingsfaktor wat verantwoordelik is vir versteuring in die bosse is mense wat bome, lote en/of takke afsaag. Respondente is van mening dat volwasse bome die grootteklas met die mees algemene voorkoms is, terwyl saailinge die skaarsste grootteklas uitmaak. Die respondente het aangedui dat geen boskultuurpraktyke toegepas word om die groei van *P. angolensis* aan te help nie. Die gevolgtrekking is dus dat die Kiaatbome tans groei sonder menslike ingryping om hul ontwikkeling te verbeter. Die kombinasie van persoonlike onderhoude en ’n ekologiese opnames het betroubare inligting rakende ekologiese prosesse opgelewer.

’n Swak positiewe, maar betekenisvolle korrelasie bestaan tussen die massa van die bogrondse lote en die penwortelmassa, wat beteken dat die lote se massa toeneem met toenemende wortelmassa. Analise van opgebergde nie-strukturele koolhidraatreserwes in die penwortel toon dat beide suiker- én styselinhoud in die penwortels die oorlewing van die boom in die struikstadium aanhelp, asook sy vinnige groei na die struikstadium. Die feit dat die saailinge minder volop is as *jongbome* en volwasse bome in hierdie studie dui aan dat verjonging van *Pterocarpus angolensis* in hierdie droë bosse maar swak is. Die bevindinge van die studie bevat inligting wat gebruik kans word (a) as die grondslag van verdere studies op die natuurlike verjonging van *Pterocarpus angolensis* in droë bosse, en (b) as inset wanneer bestuursaanbevelings vir die droë bosse van Noord Namibië ontwikkel word.

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List of abbreviations

^{0}C	Degree (s) celsius
^{14}C	Carbon-14
Al phosphates	Aluminium phosphates
AMESD	African Monitoring of the Environment for Sustainable Development
ANOVA	Analysis of variances
ASTM E100	American Society for testing and materials, Ethanol 100%
B	Boron
BA	Basal area
C	Carbon
Ca	Calcium
CA	Caprivi State Forest
CF	Community Forest
cm	Centimetre
Cu	Copper
DBH	Diameter at Breast Height (1.3 m)
ECEC	Effective Cation Exchangeable Capacity
EDTA	Ethylene diamine tetraacetic acid
Eq	Equation
Exp	Exponential
Fe	Iron

GPS	Global Positioning System
H^+	Hydrogen ion
ha	Hectare
HA	Horizon A
HB	Horizon B
HPLC	High-performance Liquid Chromatography
ICP OES	Inductively Coupled Plasma - Optical Emission Spectroscopy
INT	Iodonitrotetrazolium
K	Potassium
KCl	Potassium chloride
kg	Kilogram
km	Kilometre
ln	*Logarithm*
L-Qrt	Lower quartile
m	Metre
m^2	Square metre
m^3	Cubic metre
Mg	Magnesium
mg	Milligram
ml	Millimetre
mm	Millimetre

Mn	Manganese
MODIS	Moderate Resolution Imaging Spectroradiometer
N	Nitrogen
Na	Sodium
NaOH	Sodium hydroxide
NC	Ncumcara Community Forest
NOAA AVHRR	National Oceanic and Atmospheric Administration / Advanced Very-High-Resolution Radiometer
NPK	Nitrogen Phosphorus Potassium
NSC	Non-structural carbohydrates
Ok	Okongo Community Forest
P	Phosphorus
R	Correlation coefficient
R^2	Coefficient of determination
RB	Recently burnt
rpm	Revolutions per minute
RU	Recently unburnt
SD	Standard deviation
U-Qrt	Upper quartile
NSC	Non-structural carbohydrates
Zn	Zinc

Chapter 1: Introduction

1.1 Background

Pterocarpus angolensis, Kiaat Tree or Mukwa (Omuuva, Namibian local name) is the hardwood tree species with the most valuable timber found in the dry Miombo woodlands of North Central and East Namibia and most of the Southern African countries. It belongs to the bean family *Fabaceae* and sub-family *Papilionoideae.* The genus *Pterocarpus*, a name given to describe the unusual seed pod, "*ptera*" meaning "wing" in Greek and "*carpus*" meaning fruit in Greek. The specific name *angolensis* means "from Angola". In Namibia the species is found in Ohangwena, Kavango West, Kavango East, Zambezi (Caprivi), Oshikoto, Otjozondjupa and Omaheke regions (Graz, 2004) (Figure 1.1).

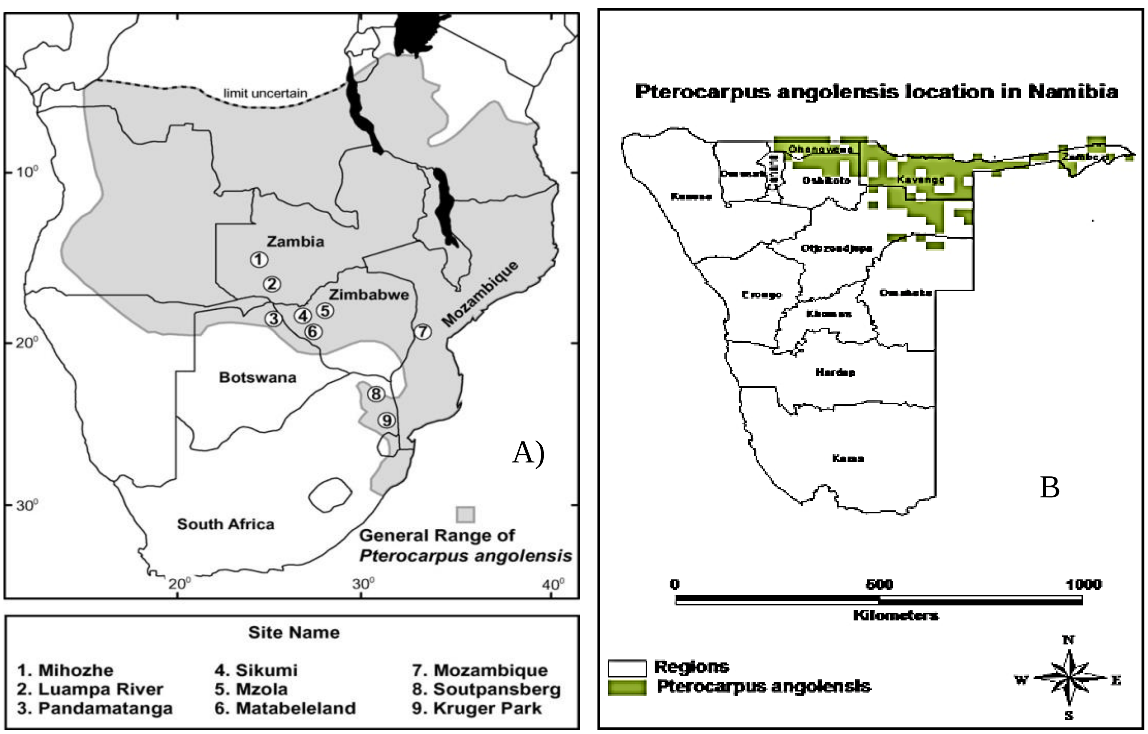


Figure 0.1: Ecological distribution of *Pterocarpus angolensis* in Southern Africa (A) and Namibia (B). (A): Therrel et al., 2007 & (B): Namibia National Remote Sensing Centre, 2013).

The Kiaat Tree has been intensively harvested during the past decades in most of the Southern African countries, especially Namibia. The successful management of this species will only be enhanced based on reliable data and knowledge regarding the growth patterns of the species within specific countries in wild populations (Desmet *et al*, 1996). Even though this tree species has been harvested at an alarming rate because of its valuable timber there are a low number of seedlings that recruit into adults in the forest and efforts to propagate it in the nurseries were unsuccessful (Shackleton, 2001). The tree development is characterised by a suffrutex stage, a sapling stage, and finally, a bole stage. The suffrutex growth stage is the time the seedling is established to the time the seedling develops its first permanent shoot, and seedlings in the suffrutex stage are called suffrutices (Graz, 1996). The suffrutex stage is characterised by below-ground carbohydrate allocation and storage in a taproot. There is little information on the factors influencing the progression of *Pterocarpus angolensis* seedling to the sapling and finally the bole stages of development. Saplings can be described as trees of 2-4 cm in diameter and more than 1 m in height but still below the bole stage, i.e. still in an understorey layer rather than competing in the canopy. This empirical study will determine factors that facilitate the progression of *Pterocarpus angolensis* seedlings through the suffrutex and sapling stages under natural regeneration in the dry forests of the three locations of northern Namibia (Okongo and Ncumcara Community Forests, and Caprivi State Forest).

1.2 Problem statement

Pterocarpus angolensis is the most valuable hardwood tree species found in North central and eastern Namibia that form part of Miombo woodlands in Southern Africa. This tree species provides construction materials, cosmetics, fire wood and medicines to local people. In northern Namibia's dry forests, this tree species has been harvested intensively for timber production without considering its natural regeneration capacity. In addition, growing seedlings in the nurseries have proven to be futile, there are no Kiaat tree seedlings grown in nurseries which mean the tree is only growing naturally (Graz, 2004). Furthermore, there is little information on factors that facilitate the progression of seedlings through suffrutex stage to bole tree stage.

The other factor which will be looked at is the impact of fire on the *Pterocarpus angolensis* regeneration. Most of the literature revealed that forest fires play a vital role on the regeneration of *Pterocarpus angolensis* in the forest by breaking seed coat to enhance seed germination. There is a great need to know the natural regeneration potential and factors facilitating seedlings development of Kiaat tree in north central and east Namibia dry forests. This would determine if there are Kiaat trees available for the next generation under the current situation.

By knowing the regeneration potential of Kiaat tree in these dry forests several silvicultural techniques can be developed for the sustainable management of Kiaat tree in the three dry forests and in Namibia as a whole.

1.3 Objectives of the study

1.3.1 Overall objective

The overall objective of this study is to investigate factors facilitating the progression from seedling stage to sapling stage then bole stage, through the suffrutex stage during the natural regeneration of *Pterocarpus angolensis* across a rainfall gradient in the dry forests of North central and East Namibia.

1.3.2 Specific objectives

1. To identify and classify different stages of seedling development according to their characteristics (i.e. seedling, suffrutex stage, sapling)
2. Regarding the fire return interval and fire resistance;
    - 2.1. To estimate the number of trees in each developmental stage in forests with increasing age after fire, across a rainfall gradient
    - 2.2. To determine the potential rate of shoot growth in terms of height after fire occurrences across a rainfall gradient
    - 2.3. To assess the tree stages most affected by fires
    - 2.4. To investigate factors influencing *Pterocarpus angolensis* tree development from sapling to bole stage.
3. Regarding the belowground carbohydrate storage of seedling and sapling stages;
    - 3.1. To characterise the different groups of carbohydrate compounds and their relative abundance in root storage organs and to investigate if this differs across a rainfall gradient or with fire history
    - 3.2. To establish the relationship between shoot biomass and root biomass and to investigate if there is a threshold below which suffrutices are prevented to advance to the bole stage.
4. Regarding access to soil water in deeper horizons and tree nutrition of seedling and sapling stages;

   4.1. To determine the relationship between taproot depth and taproot mass in the suffrutex stage
   4.2. To determine the relationship between developmental stage and taproot depth
5. Assess the main causes of woodland disturbance
6. To identify if there are management tools used to promote seedlings development
7. To assess if there are mature trees to produce seeds (seed stock)
8. To determine the ages of the seedlings / saplings by counting growth rings on the taproot neck (part between the taproot and shoot).

1.4 Thesis structure

The Thesis consists of six chapters;

Chapter 1: Introduction, highlighting the general background of *Pterocarpus angolensis*, the problem statement and the objectives of the study

Chapter 2: Highlighting the literature review

Chapter 3: Materials and Methods, highlighting methods used to carry out this study.

Chapter 4: Highlighting the results of the study

Chapter 5: Discussion of the study results

Chapter 6: Conclusions and recommendations

Chapter 2: Literature review

2.1 Introduction

Pterocarpus angolensis is a quality timber tree species whose seedlings go through a suffrutex stage to a sapling stage and then to bole stage. *Pterocarpus angolensis* adaptation is governed by rainfall regime in combination with coarse textured soils and fire tolerance. In Southern African woodlands this tree species is found in a well-drained soil, white-yellow sand, Kalahari sands, low foothills and red sand (Graz, 1996). The species grows under mean annual rainfall between 500 mm and 1 250 mm and mean minimum temperature of 20 ^{0}C in warm months and 4 ^{o}C in cold months (Von Breitenbach, 1973). The species is regarded as the most fire tolerant tree species in Miombo woodlands that grows well naturally after cultivation and burning. According to an experiment by Banda *et al.* (2006), fire is a requirement for *Pterocarpus angolensis* seed germination.

Kasumu (1998) stated that the suffrutex stage may continue for 12 years or more until the root system is able to access sufficient water and nutrients for survival of permanent shoots. On the other hand Munthali (1999) suggested seedlings enter into suffrutex stage that last for 8-15 years under natural Miombo woodlands conditions. After the suffrutex stage, sapling growth is focused on shoot growth and height rather than stem diameter growth. During die-back in dry season the shoots, lateral and hair roots cease growing and only the taproot continue to grow even under severe conditions (Kasumu, 1998).

2.2 Namibia climatic conditions

Namibia is an arid to semiarid, subtropical country in Southern Africa with average annual rainfall ranging from less than 50 mm in the West and 700 mm in the East. The erratic rains fall during summer, November to February followed by a long dry season from March to October. Namibia has a summer season from November to February with average temperatures between 20 ^{o}C and 36 ^{o}C and winter season is from May to September with average temperatures between 6 ^{o}C and 22 ^{o}C (Sweet & Burke, 2006).

2.3 Natural regeneration

Natural regeneration is the process of replacement and re-establishment of trees by self – sown seeds falling from standing trees or by vegetative recovery such as sprouting after the tree has been disturbed by fires, cutting or browsing. This regeneration is regarded as energetically the most effective method of tree replacement (Platt, 2008). *Pterocarpus angolensis* produces up to 10,000 fruits per ha **(**about 4 000 to 5 000 seeds per kg**)** but only 2% usually germinates under natural conditions (Takawira-Nyenya, 2008). According to a study by Shackleton (2001) on "Post - harvesting sulvicultural treatments in logging gaps", tending of naturally established seedlings / saplings was in general more efficient in terms of growth and survival than planting / nursery tending. Low natural regeneration is mostly attributed to sensitivity to severe fires, seed dormancy, severe drought and irregular and intermittent rainfall (Munthali, 1999).

2.4 Botanical description

Pterocarpus angolensis is classified as medium to large in size grows and can reach a height of up to 30 m. The heartwood is generally reddish to reddish-brown, while the sapwood is pale yellow to almost white. Young twigs have smooth and grey bark covered with hairs, while on the older branches and stem the bark is dark grey and rough with fissures.

According to Van Daalen *et al.,* (1992) *Pterocarpus angolensis* is a semi- ring-porous species containing terminal parenchyma; rings are not very distinct but sufficient to be counted over a wide radius. Experience is necessary to provide age estimates using date ring counting methods. Growth ring boundaries can be discriminated by the semi-ring porous structure of the vessels, a fine line of initial parenchyma, a slight difference in vessels diameter and the wood density as well as the colour from the beginning to the end of the growth band (Stahle *et al.,* 1999). The large diameter vessels congregate near the beginning of the annual growth band that are mainly solitary but less frequently found in the form of radial clusters of two to four (Stahle *et al.*, 1999). Again, Van Daalen *et al.*, (1992) stated that ^{14}C dating of trees is expensive and takes a few months (approximately four months) to complete but it is the most reliable method for dating tropical trees such as *Pterocarpus angolensis* whereby growth rings are not always formed.

2.4.1 Leaves

Pterocarpus angolensis is a strongly deciduous tree species and this is tightly synchronized with precipitation. Generally, *Pterocarpus angolensis* leaves fall from May to June and new ones emerge from September to October. Leaves consist of 5-9 pairs of sub-opposite to alternative leaflets (Stahle *et al.*, 1999).

2.4.2 Flowers

Takawira-Nyenya, (2008) stated that *Pterocarpus angolensis* starts flowering when they have a permanent stem of 15–20 years old. Flowers are pealike, orange-yellow in colour and very sweetly scented. Flowering takes place between August and December. *Pterocarpus angolensis* flowering is short, usually takes 2–3 weeks only, and pollination is performed by insects (e.g. honey bees). The phenology is tightly synchronized with the seasonality of the rainfall and flowering starting at the beginning of the rainy season. In Namibia the flowering usually occurs during September and October (Stahle *et al.*, 1999).

2.4.3 Fruits

Fruits are very distinctive; an indehiscent, circular pod with a diameter of 8-10 cm with each pod containing 1-2 small seeds. Full development of fruits usually starts when trees are about 35 years old (Takawira-Nyenya, 2008). Fruiting in Southern Africa Miombo woodlands takes place from January and ripens through to April and fruits may remain on the tree until the next flowering season (Storrs, 1995, Takawira-Nyenya, 2008). Fruit development takes 4 to 5 months (Takawira-Nyenya, 2008). Immature fruits occur as from November to March and mature fruits from March to June (Shakleton, 2001). The ripe fruit weighs 5–10 g, but because of the large wing wind transport is possible, usually up to 30 m from the mother tree. Due to the spiny centre of the fruit animals can also disperse them (Takawira-Nyenya, 2008).

2.4.4 Seeds

Pterocarpus angolensis produces hard seeds with high dormancy that can only be broken by physical rupturing of the seed coat (Sabiiti & Wein, 1987). The seed case is densely covered with harsh bristles up to 1.3 cm in length (Jɵker *et al*., 2000). The seeds have tough outer coats which inhibit and delay germination of well-developed seed under ideal conditions if not treated (Munthali, 1999). The hard and membranous fruits require scarification and degradation in order for the seed to germinate (Sabiiti & Wein, 1987).

Collection of seeds for the purpose of raising plants in a nursery is difficult because it is hard to open the pods without damaging the seed and many pods are empty (about 50% of young seed aborts). Pods can be opened manually with a pair of secateurs, but unfortunately this is time consuming and leads to seed damage and seeds may fail to germinate (Takawira-Nyenya, 2008). It was found that nicking seeds of *Pterocarpus angolensis* by removing part of the testa (hard protective layer of the seed) is the most effective method for rapid rates of germination because the seed coat prevents embryo emergence if no scarification is done. Removing part of the seed coat exposes the embryo, which is a requirement for growth (Kasumu *et al*., 2007).

Pterocarpus angolensis has seeds of very short periods of viability and low germination percentages (Maghembe, 1995). The repeated exposure to fire has consequences to seed viability (Banda *et al*., 2006). High intensity fires have been found to reduce the viability of the seeds whereas cool fires have very little influence on germination (Van Daalen, 1991). It is estimated that the limit of viability of the seed is between 1 to 2 years. Once the pod is detached from the parent tree the seed rapidly loses its viability (Vermeulen, 1990). Seeds can be stored with a low moisture content of 4-6 % for a maximum of 3 years in cold storage. Seeds from fully green fruits have lower germination percentages than seeds from fruits with brown-patched wings and a green centre (Jøker *et al*., 2000).

2.5 Ecology and distribution

The distribution of *Pterocarpus angolensis* is governed by the bioclimatic variables that limit its distribution. The Kiaat tree belongs to the leguminous plant family and is capable of fixing atmospheric nitrogen. The tree species has adapted to survive under extremes of drought, temperature, altitude, soil nutrients and tolerate fires in order to compete with other plant species (Mehl *et al.*, 2010). *Pterocarpus angolensis* is a deciduous tree that sheds its leaves during dry season in wooded grassland and savanna from sea-level up to 1 650 m. The tree requires well-drained, medium to light soils of low to moderate fertility and pH 5.5–7 (Takawira-Nyenya, 2008).

Fires as well as clearing of other plant species are vital factors in the ecology of *Pterocarpus angolensis,* as these factors positively influence the species growth by suppressing competing plants for nutrients in the soil, sunlight and space. In comparison with other trees the saplings with a thick corky bark are extremely fire resistant and can survive temperatures of up to 450 °C. This made *Pterocarpus angolensis* a pioneer in areas where fires occurred (Mehl *et al.*, 2010).

Pterocarpus angolensis grows in southern and eastern Africa in areas where there is a dry season contrasting with a wet season and grows best where it is warm and free of frost. It grows well in deep sandy soil or well drained rocky slopes where rainfall is above 500 mm per year (Graz, 2004). *Pterocarpus angolensis* growing on good sites with full light live up to 100 years, by which age they are about 20 m tall, with a crown diameter of 10–12 m and a bole diameter of 50–60 cm; bark thickness 1.5–2 cm and a sapwood thickness of 5 cm (Takawira-Nyenya, 2008). Factors that limit the distribution of selected savannah tree species including *Pterocarpus angolensis* are complex, operate at different scales and are not reflected by their current distribution patterns (Graz, 2004).

2.6 Factors affecting germination

2.6.1 Soil

The soils of Miombo woodlands are poor in organic matter, nitrogen and phosphorus and generally have low cation exchange capacity. The lower nitrogen and phosphorus levels in the Miombo soils are due to annual fires which consume organic matter. Fortunately, *Pterocarpus angolensis* possesses both vesicular-arbuscular mycorrhizae and functional N-fixing root nodules ensuring that the species is able to efficiently utilize available nutrients (Mehl *et al.*, 2010). Both rhizobium and mycorrhizal associations influence germination (Jøker *et al*., 2000**).** A study on unfertilized *Pterocarpus angolensis* seedlings raised in the nursery found adequate nitrogen levels in the leaves that are likely to have come from nitrogen fixed by the plants themselves (Munyanziza *&* Oldeman, 1995).

2.6.2 Fire

Fire is regarded as a germination stimulant that can rupture the protective fruit to allow the water to enter thereby triggering the germination process (Sabiiti & Wein, 1987). The removal of grassy layer and wings and bristles of the fruit in the ecosystem by a cool fire can cause the seed to come into contact with the ground and enhance seed germination (Van Daalen, 1991).

Nutrients such as phosphorus and nitrogen are released during fires and made available to seedlings and mature *Pterocarpus angolensis* trees, promoting nitrogen fixation (Mehl *et al.*, 2010). Fires contribute to pruning side branches and multiple stems (Takawira-Nyenya, 2008).

A study by Banda *et al.*, (2006) on *Pterocarpus angolensis* germination rate of seeds from husked and unhusked fruits found that seed germination and persistence in unhusked fruits are maximized by moderate exposure to fire. Seeds without husks persist in the soil yet continued to germinate even after 18 months in wet soil indicating potentially long soil longevity.

Germination of husked seeds decreased with increasing exposure to fires meaning the least burnt plots had the highest germination rate. Repeated moderate exposure to fire enhances the capacity of seeds to emerge from fruits. Seeds from unburnt and unhusked fruits do not germinate and have poorer soil longevity than those exposed to moderate fire (Banda *et al*., 2006). Extreme exposure to fire results in poor seed germination rates due to direct fire damage and consequent mortality of seeds. Seed exposure to moderate fire intensities assist in breaking down the woody fruit and facilitate germination. Low intensity fire is vital for seed germination of both husked and unhusked fruits.

A study by Caro *et al.*, (2005) found that there was lower *Pterocarpus angolensis* recruitment in protected areas where the grass cover was thick and parent tree canopy cover was profuse. This suggests that *Pterocarpus angolensis* seedlings suffer from competition for light. Again, burnt areas contain fewer recruits than unburnt areas; this may be an artefact of fire mortality of small suffrutices. This is an indication that full light, absence of high intensity fire, absence of root competition, adequate supply of mineral nutrients all promote rapid growth from seedlings to sapling stage.

In addition, the low density of *Pterocarpus angolensis* recruits in protected areas may be due to browsing by large numbers of animals (Caro *et al.*, 2005). On the other hand fire and clearing of vegetation for cultivation remove competing plants species that adversely affect the growth and development of *Pterocarpus angolensis* (Boaler, 1966).

2.6.3 Climate

The growth of *Pterocarpus angolensis* is sensitive to climate especially with regards to temperature and relative humidity. This may be due to the range of its root depths that lie between 30 cm and 200 cm which have better access to ground water (Vermeulen, 1990). However, Takawira-Nyenya (2008) stated that rainfall is more important than a permanent subterranean water supply and under conditions of exceptional competition for ephemeral water resources the tree does not survive. High temperature is also one of the major factors contributing to the lack of *Pterocarpus angolensis* natural recruitment while low temperature (frost) affect younger trees, causing them to die back. The tree is not resistant to frost, although older trees survive very light frost events (Banda *et al*., 2006, Graz, 2004).

Drought causes *Pterocarpus angolensis* stress, which results in secondary attack by other biotic agents, insects and fungi and weakening them, increasing their vulnerability to subsequent periods of drought. The shallow root system of *Pterocarpus angolensis* when in competition with a dense grass or shrub layer contributes to susceptibility to drought and diseases such as Mukwa when the annual rainfall is lower than 500 mm (Mehl *et al.*, 2010). Drought reduces fire severity but increases water stress on germinated seedlings. Wet periods foster increases in plant biomass and subsequently more severe fires, but favours seed germination and establishment **(**Banda *et al*., 2006).

2.6.4 Diseases

The most important *Pterocarpus angolensis* disease is Mukwa diseases which has a range of symptoms, the most prominent being blight and die-back of affected trees. The disease is attributed to a fungus *Fusarium oxysporum* (schltdl). *Fusarium oxysporum* is a well-known pathogen causing wilt diseases on leaves, crown and root rots of a wide variety of plants (Mehl *et al.*, 2010). Many young *Pterocarpus angolensis* trees are easily infected by fungal infections on the leaves, manifested as small, circular black dots (Thunström, 2012).

2.7 Seedlings and root growth stages

Initial *Pterocarpus angolensis* seedlings develop a taproot of between 45 cm and 90 cm in the first growing season. The taproot has a thickened portion from a shallow depth, usually down to a depth of approximately 60 cm and then tapers off rapidly. The shoots reach about 15 cm length in the first year and often die back in the dry season (Takawira-Nyenya, 2008).

The die-back occurs each year until the root system has sufficiently grown to support the shoot to withstand the dry season (Nyondo, 2002). Under natural condition**s** seeds of Miombo tree species germinate during rainy season but shoot growth slow**s** as the seedlings allocate biomass to root development prior to shoot elongation. Again, suffrutices are unable to grow to sapling size until their root system has developed enough to reach moisture reserves held in the soils through the dry season (Boaler, 1966).

Deciduous tree species including *Pterocarpus angolensis* contain carbohydrate stores to sustain respiration, facilitate replacement of lost tissues and to endure periodic stresses such as drought (Newell et al., 2002, Veneklaas & den Ouden 2005). Carbohydrate storage accumulation in tree roots support respiration cost during die-back of shoots (Poorter & Katajima, 2007). The allocation of carbon to storage ensures tree to withstand stress and disturbances caused by fires, browsing and pathogens. According to Newell et al., (2002), tree roots store more starch than sugars whereas branches store more sugars than starch.

Many seedlings do not survive the suffrutex stage because of drought, burning, nutrient deficiencies (particularly boron) and damage by intensive fires (Takawira-Nyenya, 2008). The seedlings stage is mostly prone to damage by animals, particularly larger mammals such as elephants that browse on the younger leaves and chew the bark of saplings while wild pigs dig up plants to reach the fleshly taproot (Graz, 2004). Initial shoot growth of saplings often forms a zigzag pattern because of the yearly die-back of the 10 cm top shoot. After the suffrutex stage, the growth is fast, up to over 2 m in one year, and the tree rapidly reaches a height where it cannot be reached by most browsing animals. During the first decade following the suffrutex stage, height rather than diameter increases, while in the second decade the diameter increases more rapidly (Takawira-Nyenya, 2008).

Mwitwa *et al*. (2008) conducted a study on the variation of shoot die-back and root biomass of the *Pterocarpus angolensis* provenance from Namibia, Malawi and Zambia for two shoot die-back seasons. The experiment indicated that within provenance family effect was not significant in the first shoot die-back season but significant in the second that might be as a result of different latitudes between the three provenances.

The non-significant phenotype correlation between shoot die-back and root biomass shows that shoot die-back is not determined by taproot size or taproot depth. Conditions of full light and removal of root competition are ideal for the production of saplings from suffrutices. Better shoot length growth of *Pterocarpus angolensis* in burnt area compared to unburnt area is due to additional of mineral nutrients to the soil from the ash. *Pterocarpus angolensis* needs a well-established root system before it grows to a sapling size from suffrutices and is further subject to the values of environmental factors such as light, fires, root competition and mineral nutrition. In full light the plant can produce shoots of approximately 1 m length each growth season of which the 10 cm top shoot dies back at the end of the growing season (Boaler, 1966).

When all competing vegetation were removed by digging out their roots, protection from burning and NPK fertilizer added to the soil around each suffrutex, 13 suffrutices out of 45 developed into saplings in one year. Under natural conditions, nutrient concentration in the taproot might be contributing to the different stages of suffrutices development into saplings and subsequently to bole tree stage (Boaler, 1966).

2.8 Vegetative propagation

Pterocarpus angolensis can be propagated by seed and by cuttings (Takawira-Nyenya, 2008). Cuttings (e.g. 2 m long and at least 2 mm in diameter) can be planted at the beginning of the rainy season but success rates vary from 0–30 % (Takawira-Nyenya, 2008). Cuttings frequently produce shoots that draw food from their stored food reserves but roots are not formed. The root formation depends on their ability to obtain water for the developing plant before reserves within the wood of the cutting are exhausted. This is rare because it is the taproot of young plants that perform this function in the pre-rain flush (Boaler, 1966). Planting of truncheons 10 cm in diameter into 1 m deep plant holes with some coarse river sand at the bottom has also been recommended (Takawira-Nyenya, 2008).

Yearly die-back, a long suffrutex stage and damage to the root system when transplanting are other nursery problems that are difficult to solve. Again, the extensive and deep root development results in the tree being difficult to propagate in the nursery (Kasumu, 1998). Therefore, if *Pterocarpus angolensis* is to be grown in plantation format, it would be easier to establish these plantations at natural plots where plants in the suffrutex stage are already present. According to Orwa *et al.* (2009), small plantations of *Pterocarpus angolensis* as a viable option have been successfully planted in Mozambique.

2.9 *Pterocarpus angolensis* natural regeneration status in Namibia dry forest

Pterocarpus angolensis is an important component of dry woodland savanna of Northern Namibia; unfortunately no management particularly on natural regeneration has been implemented in the country. The dry conditions of Namibia woodland is associated with relatively slow growth rates and poor regeneration particularly in the nutrient poor deep Kalahari sands (Jarvis, 2011).

Several research projects have been conducted in some Southern African countries on vegetative propagation of *Pterocarpus angolensis* through seed germination in the nurseries, coppicing and cuttings but very few on the natural regeneration. Most of these research projects have been carried out on factors contributing to suffrutex stage but not on the factors that contribute to the seedlings progression through suffrutex stage to sapling stage then bole tree stage. Again, nothing has been researched to determine carbohydrate storage or nutrient contents in different stages of seedling development. *Pterocarpus angolensis* in Namibia grows in areas of limited and irregular rainfall (i.e. dry forest) that might have a different growth behaviour and different root architecture from those growing in areas of more regular rainfall.

In Namibia, specific research on *Pterocarpus angolensis* forms part of a trial to investigate the effect of fires on different tree species (including *Pterocarpus angolensis).* This trial has been monitored for several years but concrete results are not yet available. Other research conducted in Namibia dry forest are not empirical based research. Consequently, empirical evidence on the natural regeneration of *Pterocarpus angolensis* is vital and contributing factors such as fires, animal browsing and tramping, vegetation clearing, root carbohydrates storage, soil nutrient contents and textures that influence the regeneration of the tree in the Namibia dry forest.

2.10. Forest management in Namibia

According to the Development Forestry Policy for Namibia 2001, forest management is being implemented with full participation of the local communities. Forest resources are managed in a sustainable manner to meet the current needs, maintain and increase forest productivity potential level and using forest resources without damaging its resilience. Sustainable management of forest resources is to ensure security of supply and efficient utilisation of forest raw materials. The Directorate of Forestry is mandated to ensure full participation of local community in forest management and practices by private forest ownership are transparent and accountable. The Forest Act No. 12 of 2001 as amended Forest Act No.13 of 2005 Part III provides the creation of Classified Forests that includes State Forest managed by State and Community Forests managed by local communities (The Namibian Parliament 2001).

Community forests play a vital role in Namibia's conservation goals, monitoring and effective implementation of community based natural resource management (CBNRM). Community forests implementation is to benefit the local community by providing them the opportunity to develop a forest management plan to determine the utilisation of forest resources. The income generated from the use of resources within community forest is directly benefiting the community. Community forests have been developed as integrated land and resource-use systems in co-operation and co-ordination with all other relevant stakeholders (Dusenberg, 2011). In addition the Forest Act Part VI made provision for forest fire management whereby a fire management committee is established to prepare fire management plans and ensure its implementation (The Namibian Parliament 2001). One of the fire management activities implemented is the construction of fire cutlines.

Summary

The literature review indicates that *Pterocarpus angolensis* in the dry forest is mostly influenced by the fire regime, rainfall, nutrient availability and medium to light soils of low to moderate fertility. In addition, low natural regeneration in the dry forests is mostly attributed to sensitivity to severe fires, seed dormancy, frost, diseases, severe drought and irregular and intermitted rainfall as well as competition with other plants. High intensity fires has a negative impact on the natural regeneration of the tree as it burn seeds and kill seedlings and saplings but low to moderate intensity fires promote seed germination. *Pterocarpus angolensis* seedlings undergo a suffrutex stage; the yearly die-back of the shoot while the taproot accumulates enough carbohydrate reserves to supply and support the shoot to withstand the dry season. Most of the attempts to raise *Pterocarpus angolensis* seedlings in the nurseries have not produced satisfactory results and the best alternative might be to develop techniques to promote natural regeneration and tree development through the suffrutex and sapling stages.

Chapter 3: Materials and Methods

3.1 Introduction

This chapter highlights selected study locations, fire history treatments, and plots where the data was collected. In addition, describing how several samples were collected and measured as well as laboratory methodologies used to analyse the samples and statistical software used to analyse the data.

3.2 Study locations

Three study locations were selected according to their different rainfall gradient; Okongo and Ncumcara Community Forests and Caprivi State Forest. These are dry forests located in the North central and eastern parts of Namibia in Ohangwena**,** Kavango West and Zambezi Regions respectively at the Namibia – Angolan – Zambia borders (Figure 3.1). Okongo forest is 149 km from Eenhana, the Capital Town of Ohangwena region and 49 km from Okongo settlement. The size of the forest is 75 518 ha including the veterinary quarantine camp. Okongo and Ncumcara dry forests were declared as Community Forests in 2006 (Government Gazette no. 3590) according to the Forest Act of 2001 as amended Act no. 13 of 2005 of Namibia**.** Ncumcara Community Forest is 30 km south of Rundu Town. The total area of Ncumcara Forest is 15 216 ha. Caprivi State Forest is about 140 000 ha in size, located 10 km west of Katima Mulilo Town**.** Currently, there are elected Forest Management Committees responsible for the management of the forest resources in Okongo and Ncumcara Community Forests while Caprivi State Forest is under government management.

3.2.1 Vegetation

The most dominant tree species in the three study locations are *Baikiaea plurijuga*, *Pterocarpus angolensis*, *Burkea africana*, *Combretum collinum*, *Dialium engleranum*, *Guibourtia coleosperma* and *Terminalia sericea*. There are also a considerable number of species in the shrub layer such as *Bauhinia petersiana*, *Baphia massaiensis*, *Terminalia sericea*, *Croton gratissimus* and *Ochna pulchra* (Otsub, 2007, Angombe *et al.*, 2000, and Chakanga *et al.*, 1998). The comparison between the forests at the three study locations is difficult because of different measurement techniques used and because the published data is not all in the same format. In Okongo forest, the mean volume and the mean number of trees of the whole forest is estimated to be 43.2 m^3 / ha and 209.8 stems / ha respectively (Angombe *et al.*, 2000).

There are on average 4 603 shrubs and tree saplings per hectare in the shrub layer. Generally, the regeneration of tree species is good but the regeneration of *Pterocarpus angolensis* is sparse (Angombe *et al.,* 2000). According to the Inventory report by Angombe *et al.,* (2000) tree volume of *Pterocarpus angolensis* trees in the harvestable diameter classes (DBH 45 cm and above) is estimated at 48 100 m^3 in the inventoried 55 918 ha of Okongo forest which is 0.86 m^3 / ha. The average log volume (saw-log volume) is estimated at 15 340 m^3 which is 0.27 m^3 / ha. The average height of the dominant tree species is 10 m. *Pterocarpus angolensis* mean height is 11 m, ranging from 3.3 m to 19.4 m and occupies roughly 12.3% of the total area of the forest. The stand density of *Pterocarpus angolensis* of all size classes is estimated at 31.7 stems / ha (Angombe *et al.,* 2000).

In Ncumcara Community Forest, there are an estimated total number of 1 964 000 trees with 129 trees per ha and 12 m^3 per ha of stem volume. The total number of dead trees is 170 000 which is 11 trees per ha. The main tree species are *Burkea africana* (47%), *Pterocarpus angolensis* (15%), *Dialium angleranum* (8%), *Guibourtia coleosperma* (5%), *Terminalia sericea* (4%) and *Schinziophyton rautanenii* (4%). Seedling regeneration of the most important three species *Burkea africana*, *Pterocarpus angolensis* and *Dialium angleranum* is 1 200 seedlings per ha. According to this data the stand density of *Pterocarpus angolensis* should be 19 trees per ha (Otsub, 2007).

There is no resource assessment (inventory) carried out in the Caprivi State Forest. The only resource assessment information available is that carried out in the whole of Zambezi Region (former Caprivi Region). The most common tree species are *Terminalia sericea*, on average 14.11 stems per ha, *Burkea africana* 13.6 stems per ha, *Colophospermum mopane* 12.76 stems per ha and *Baikiaea plurijuga* 7.37 stems per ha and *Pterocarpus angolensis* 2.24 stems per ha and a mean tree volume of 0.59 m^3 / ha.. The mean saw log timber volume of *Pterocarpus angolensis* trees is 0.06 m^3 / ha. The resource assessment also stated that 2.8% of the *Pterocarpus angolensis* trees are dying or have already died from fires (Chakanga *et al*., 1998). In Caprivi, there is less than one *Pterocarpus angolensis* seedlings per ha (according to Chakanga's 1998 study), which may imply that the tree is very susceptible to frequent annual forest fires that occurs in the area.

In addition, the removal of large trees in the past years for commercial purposes might result in low regeneration and low number of small trees at present. Removal of big trees mainly by humans disturbs the ecosystem and enables *Pterocarpus angolensis* trees to regenerate (Chakanga *et al*., 1998).

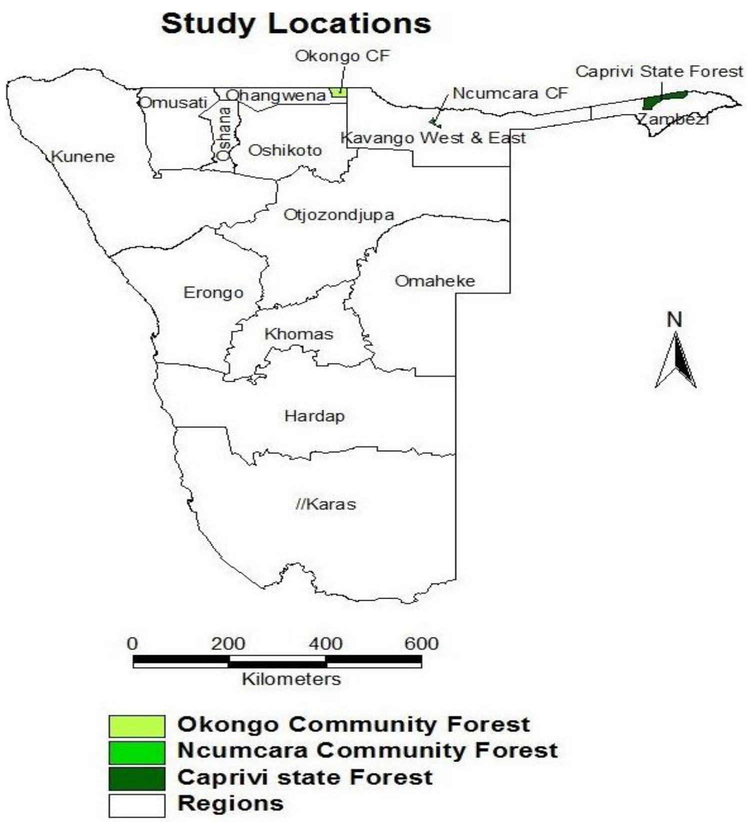


Figure 0.1: Study locations in the Namibian map (Namibia National Remote Sensing Centre, 2013).

3.2.2 Land use

The Okongo and Ncumcara Community Forests have been used as cattle posts and hunting areas but now people have started crop cultivation. As a result, clearing of the forest is happening at an alarming rate to establish field crops especially at Okongo Community Forest and thus putting much pressure on forest resources. Caprivi State Forest is under government protection and no other land use activities being carried out except grazing.

3.2.3 Climatic conditions

The mean annual rainfall of Okongo forest is characterized by a long dry season from March to October is between 450 mm and 650 mm while November to February is the wet season.

The monthly average rainfall ranges from 30 mm to 140 mm between the months of October and April. The monthly average maximum temperature ranges from 16 ^{o}C to 23 ^{o}C during summer while the monthly average minimum temperature ranges from 8 ^{o}C to 17 ^{o}C during winter. Frost occurs annually between June and August (Mouton, 2008).

The average minimum temperature of Ncumcara Community Forest ranges from 6 ^{o}C during cold months, June to August and the average maximum can reach 35 ^{o}C during warm months, September to February. The number of days with below 0 ^{o}C varies from 5 to 10 per year. The total annual rainfall average is between 550 - 580 mm (Otsub, 2007).

Caprivi State Forest, the monthly average temperature ranges from a minimum of 4 ^{o}C during cold months of May to August to a maximum of 33 ^{o}C during warm months of September to February. The total annual average rainfall is 700 mm. The average elevation is about 930 m above sea level (Chakanga *et al*., 1998).

3.2.4 Soil conditions

The three study locations are part of the North-Western Kalahari. The soil is mainly ferralic arenosols overlying sands and calcrete. Soil texture is sandy and the soil colour differs due to different mineral content. Due to the coarse texture, the soils have high drainage and low nutrient content. The landscape is flat with some small dune valleys and sand dunes. The dominant soil textures in the three study locations ranges from sandy loam to loamy clay. Most of the areas have soils derived from deep Kalahari sands (Mouton, 2008)**.**

3.3. Field work

The field work was conducted during summer (September to October), before the flowering and rainy season which meant that suffrutices still had to produce shoots. The research data was collected from three study locations at Okongo Community Forest, Ncumcara Community Forest and Caprivi State Forest. The name of Ncumcara in this Thesis refers to Ncumcara Community Forest, Okongo refers to Okongo Community Forest whereas Caprivi refers to Caprivi State Forest. Two fire history treatments were allocated to each study location. The two fire history treatments were allocated according to their fire intervals; recently burnt (RB), i.e. 1-2 years post-forest fires and areas that had been left unburnt in the recent past , i.e. 4 + years post-forest fires and hereafter referred to as “recently unburnt” (RU) (Figure 3.2).

3.4 Remote sensing data

The National Remote Sensing Centre in the Directorate of Forestry provided the information maps on the forest fires history in the three study locations. The Centre had been mapping burned areas in Namibia since 1994 using NOAA AVHRR and MODIS satellite data. Currently, mapping is done from satellite image data received on the AMESD (African Monitoring of the Environment for Sustainable Development) system at the National Remote Sensing Centre. Four maps were produced for each fire history treatment and coordinates identified. Then the maps and coordinates were used in the field to identify fire history treatments during reconnaissance.

In September 2013 a reconnaissance was carried out at the three locations to identify plots of *Pterocarpus angolensis* before the field work started. Unfortunately, at the time of the field work some of the fire history treatment plots identified during reconnaissance were found burnt, making it impossible to collect the data. As a result new fire history treatment plots had to be identified. Some of the late identified plots mainly in recently unburnt treatments were close to the villages and road because most part of the forest has been burnt.

3.5 Meteorological data

Even though weather data such as average annual rainfall and minimum and maximum temperatures were provided in the literature it was necessary to visit the National Meteorological office to get the actual weather data. The average annual rainfall and temperature of the three study locations are vital for this study because the three study locations are chosen to represent a rainfall gradient. The weather data for the last nine years were obtained from Windhoek Meteorological office. These weather data are from the nearest weather stations, the Okongo Community Forest weather data is from Ondangwa, Ncumcara Community Forest from Rundu and Caprivi State Forest from Katima Mulilo weather stations (Figures 3.3 & 3.4). However, some of the monthly data of the year are missing and the monthly average values were used to replace the missing data (Namibia National Meteorological Division Office; 2013).

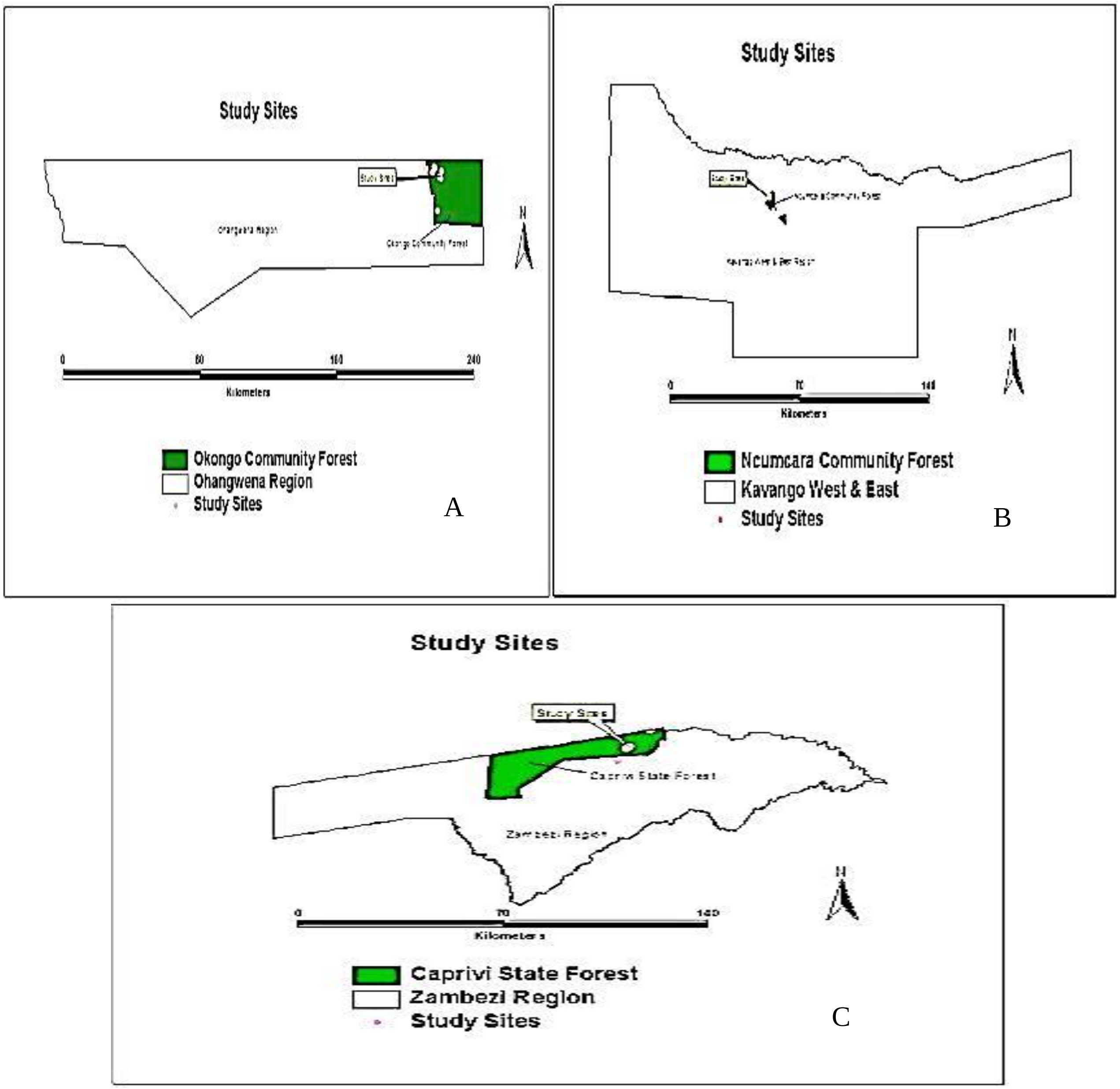


Figure 0.2: Fire history treatments (Study sites) A = Okongo Community Forest, B = Ncumcara Community Forest & C = Caprivi state Forest (Namibia National Remote Sensing Centre, 2013)

3.6 Observations

Observations were done in all the plots to find out disturbances of the *Pterocarpus angolensis* trees. These observations were mainly focused on the evidence of damage to the tree by forest fires, animals, human beings, presence of symptoms of diseases and harmful insects. The disturbance evidences were observed by looking for defoliation, stem holes, debarking, stump, tree burnt scars, rotten stem parts and dead or drying seedling and sapling shoots.

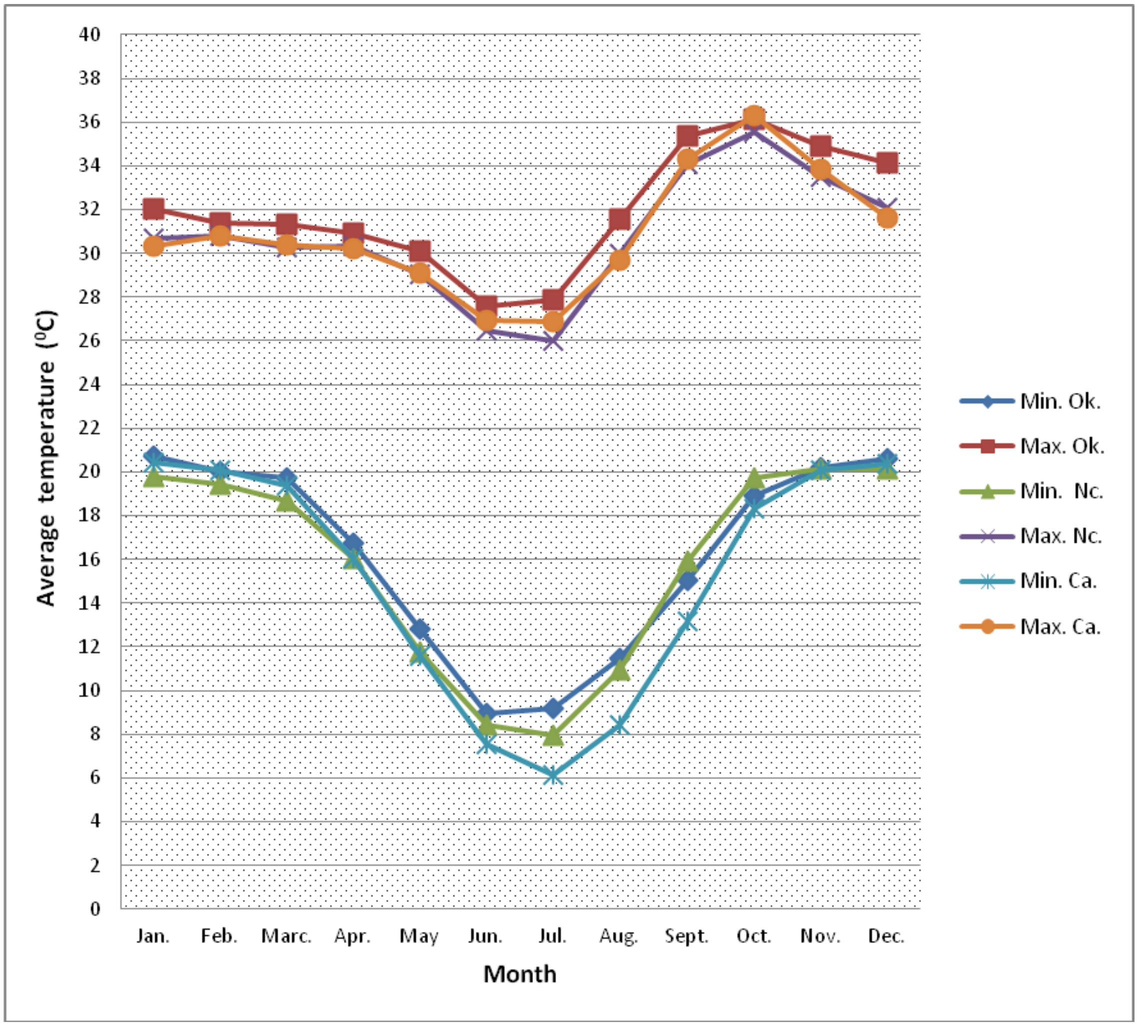


Figure 0.3: Monthly average temperature for the three Northern Namibia dry forests. Ok – Okongo, Nc – Ncumcara, Ca - Caprivi (Namibia National Meteorological Division Office; 2013).

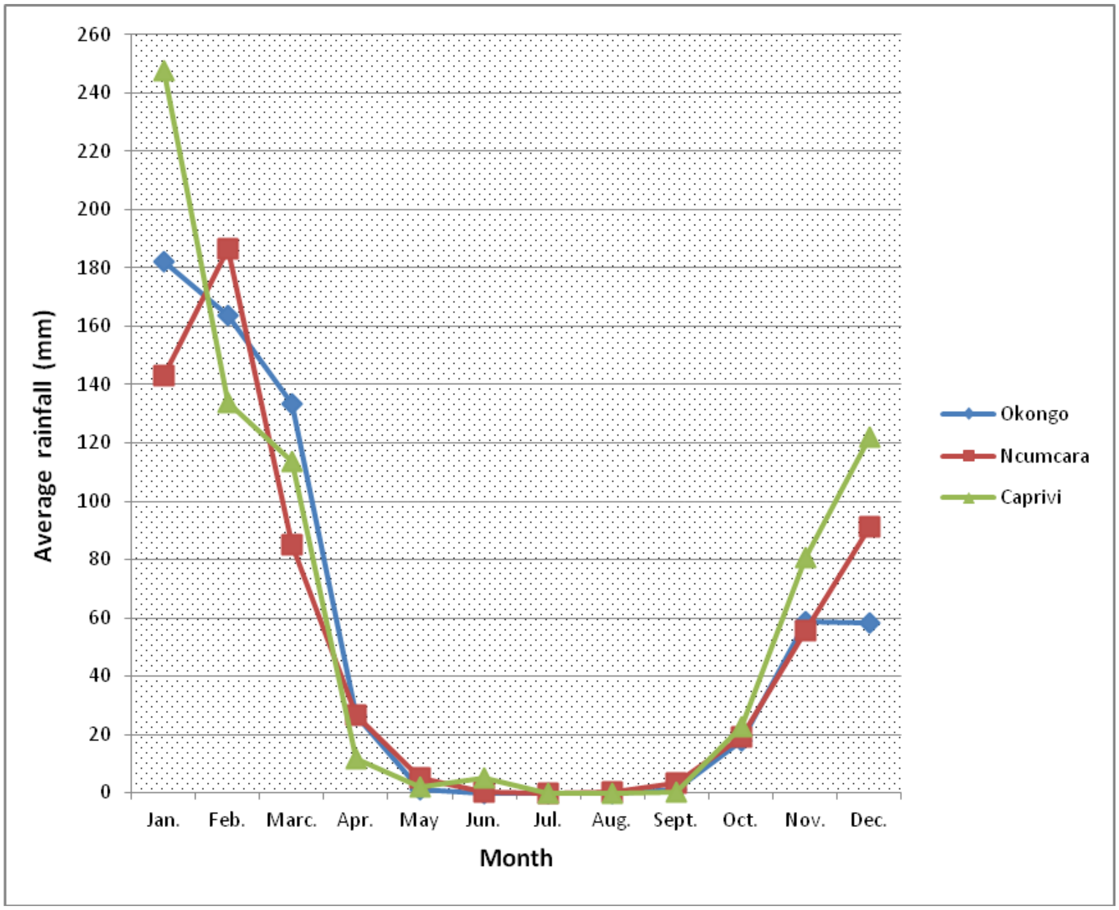


Figure 0.4: Monthly average rainfall for the three Northern Namibia dry forests (Namibia National Meteorological Division Office; 2013)

3.7 Interview data

3.7.1 Structure of questionnaires

A questionnaire survey was used to interview 20 individuals per study location to find out current management techniques being used to promote natural regeneration, factors affecting regeneration, the rate of regeneration and the period since last fires. The respondents were selected based on their knowledge of the forest conditions and events. Random sample techniques were not used because of the small population size and the interviewee's specific knowledge requirement to be surveyed. In total 60 questionnaires were completed. Interviews were carried out in areas where *Pterocarpus angolensis* trees commonly occur with people associated with each forest site.

3.7.2 Administration of questionnaires

A sample survey that involved single-visit to households or individuals was used (Figure 3.5). This kind of survey is appropriate because it can be applied to small, medium and large population in size and leads to better accuracy resulting from better quality of enumeration and supervision. The questionnaire survey consisted of written questions, conversation of questions and answers with respondents which is a semi-structured interview with closed and open questions.

The interview was conducted face to face in homesteads and community centres whereby each interviewee was interviewed individually using questionnaires. This type of interview is referred to as semi-structured interview whereby individual interviewee freely discloses any information. Again, individuals can be asked follow – up questions (Cohen, & Crabtree, 2006). The questionnaire questions were open-ended to avoid biases and provide more conventional estimate of desired information. According to Nichols (1990), open-ended questions are also statistically more efficient compared to other type of questionnaires (Appendix 1).

Figure 0.5: The interview with Shingalamwe village headman (Sub-kuta) around Caprivi State Forest.

3.4 Sampling

At each study location four sampling plots were allocated to each fire history treatment based on the availability of *Pterocarpus angolensis* trees and accessibility (Figure 3.6; A. B. C). GPS was used to demarcate sampling plots by taking coordinates. To facilitate visibility of boundaries for sampling in field, we used 12 square blocks of 20 m x 20 m = 400 m^2 each, which, when put together, made up one plot of 4,800 m^2 (0.48 ha) in total (Table 3.1). The four plots per fire history treatment is 0.48 x 4 = 1.92 ha meaning one fire history treatment is equal to 1.92 ha while two fire history treatments per location is 1.92 x 2 = 3.84 ha per location, in total 11.52 ha for all three study locations.

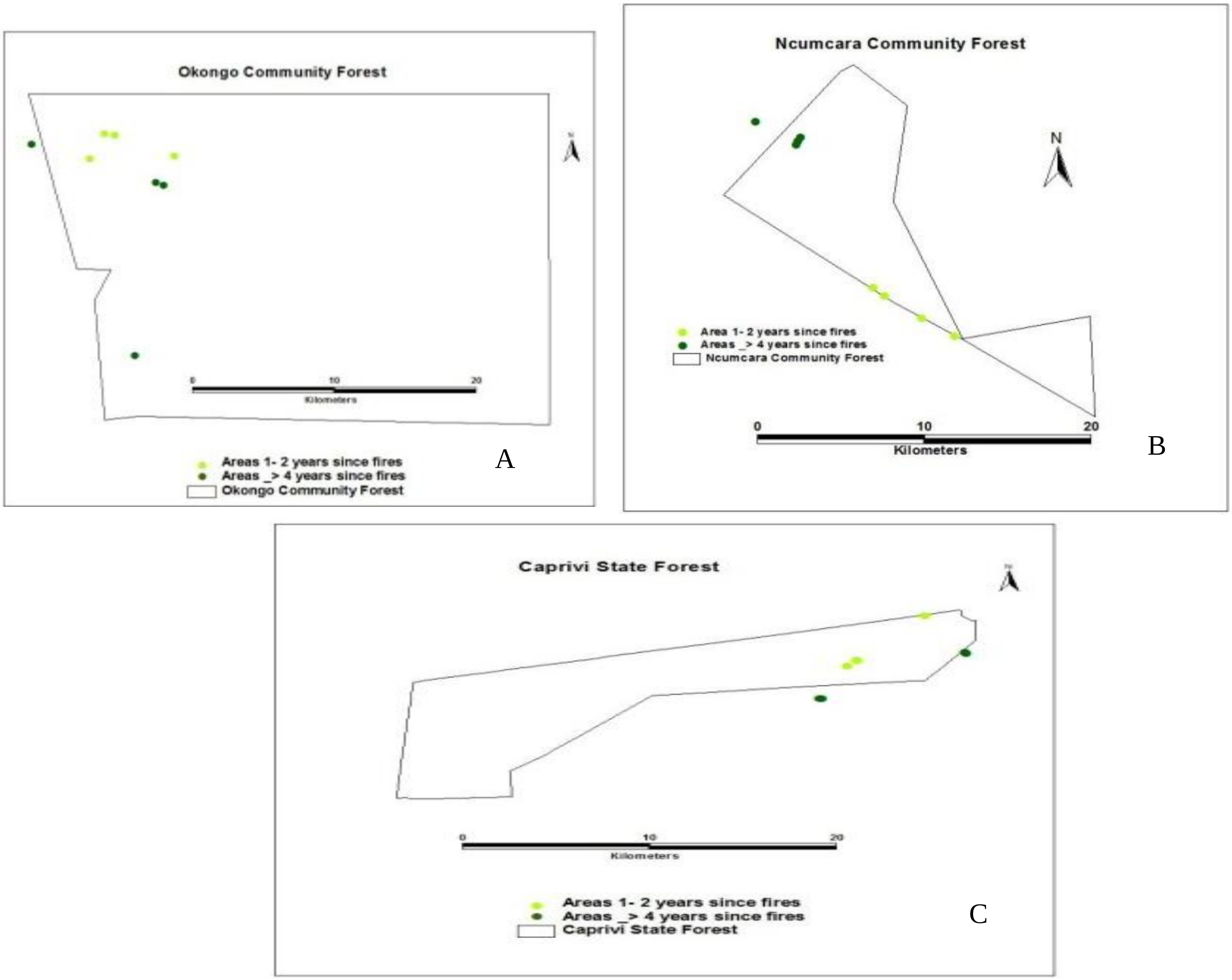


Figure 0.6: A, B & C: Fire history treatment as per post-forest fires intervals including sampling plots (Namibia National Remote Sensing Centre, 2013). Note that some plots had to be located just outside some of the administrative boundaries, but care was taken to ensure that the forest condition remained similar to the other plots.

Table 0.1: Sampling plot design showing the subdivision into 12 sub-plots.

1	2	3	4	5	6
7	8	9	10	11	12

3.4.1 Vegetation sampling (Inventory)

The inventory of live seedlings, saplings and mature trees were carried out in the four sampling plots of each fire history treatment to determine the number of *Pterocarpus angolensis* trees. Trees were recorded according to their three stages shoot height: seedlings, saplings and bole (mature trees).

Trees were categorised based on their shoot height as follows: 0 – 1 m seedlings, 1.1 – 3 m saplings and more than 3 m mature trees (bole trees). So, all trees that are more than 3 m height were recorded as greater than 3 m. All *Pterocarpus angolensis* trees, young and mature, found within the sampling plot were counted. The height and diameter of the saplings from 1.3 m to 3 m were recorded while seedlings and saplings of 0.0 to 1.2 m only their height was recorded. Only diameters of trees more than 3 m high were recorded. Tree conditions such as evidence of damage were also recorded. The form used to record tree attributes can be seen in Appendix 2.

Stand density and basal area of the *Pterocarpus angolensis* trees were determined by calculating:

Equation 1: Stocking

$$Stocking = \frac{\sum Trees\ in\ plot}{Plot\ size} \qquad \text{trees/ha}$$

Equation 2: Tree Basal Area $= \frac{\sum BA}{10000 * plot\ size}$

$$Where \quad BA = \frac{\pi(DBH^2)}{4} \qquad \text{m}^2\text{/ha}$$

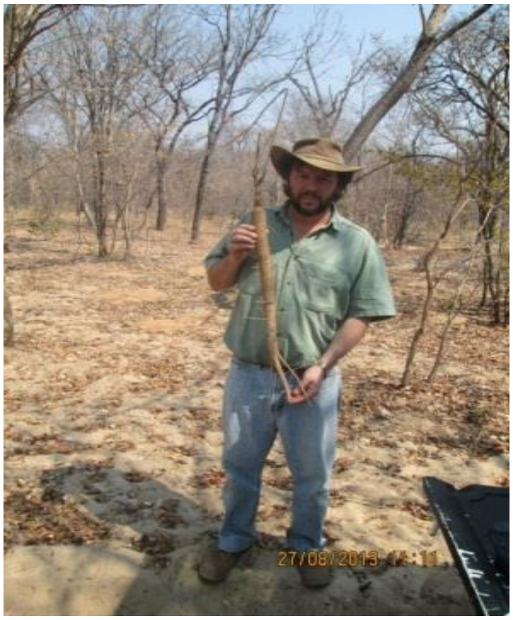
3.4.2 Destructive vegetative sampling

This sampling focused only on seedlings and saplings from 0 m to 3 m shoot height. The selection was not randomly done because most of the sampling plots did not have many seedlings and saplings. Then a maximum of 10 seedlings or saplings together from 0 m to 3 m shoot height per sampling plot were removed by uprooting the whole plant up to 1 m of the taproot depth or the beginning of forked lateral roots. However, a maximum of 10 seedlings or saplings could not be found in some of the sampling plots. Appendix 3 presents the form used for recording to this data.

3.4.2.1 Shoots and taproots

All the shoots of the removed seedlings and saplings were weighed to determine their above-ground biomass. All *Pterocarpus angolensis* seedlings have a tuber that forms part of the main taproot, and the shape of the taproot usually resembles that of an oversized carrot. Lateral roots were cut off where they fork from the taproot, and the main taproot was cut off at 1 m depth (or at major forks if this occurred above 1 m) (Figure 3.7). After dusting off the sand on the main taproot, the fresh mass and maximum diameter at the thickest part of the taproot was recorded. After cutting off the shoots from the taproot the corer was used to drill into the taproot to draw core samples for chemical analysis.

One core sample was taken from taproots of less than 50 cm in length whereas two core samples taken from taproot of more than 50 cm in length, one core sample on the top and second one at the bottom. The core samples were taken for laboratory analysis to determine taproot non-structural carbohydrates (NSC) storage.

Taproot in suffrutex (seedling) stage   Taproot after suffrutex stage (sapling)

Figure 0.7: Taproot development stages, taproot at suffrutex (seedling) stage has a carrot shape while after suffrutex i.e. sapling stage lateral roots develop.

3.4.2.2 Taproot necks

The neck (part between the taproot and shoot) of each seedling or sapling (Figure 3.8) was cut off into disc shape. The cross-section of the neck transverse surfaces ranged from 1.4 cm to 7.0 cm. Stahle *et al.* (1999) stated that the cross-section with a transverse surface of more than 5 cm of the sample is required for the analysis because of the occasional formation of extremely narrow or discontinuous rings. Then the neck disc mass, diameter and height were measured.

Some of the seedlings and saplings did not have necks while some of the necks were damaged having holes and could not be considered for analysis. Neck disc samples were taken to determine the approximate age of the seedling or sapling spent in the suffrutex stage using cross-dating techniques in the laboratory. The literature review revealed that Kiaat tree cross-dating was performed on stem disc samples which might exclude the ages the tree spent in suffrutex stage (Fichtler *et al.*, 2004). All the samples were packed and sent from Namibia to Stellenbosch University in South Africa for laboratory analysis.

Figure 0.8: Taproot with well distinctive neck; the position of the secateurs indicate ground level. (photo: F. Kayofa 2013).

3.4.3 Soil samplings

Soil samples were collected from three points in each sampling plot from the soil surface level between 0 – 20 cm the top soil (A-Horizon; HA) and bottom layer of 30 – 40 cm the sub-soil (B-Horizon; HB) using the cylindrical samplers (Figure 3.9). The litter on the soil surface were removed before the cylindrical samplers inserted into the soil to avoid mixing litter with soil samples. A stick of 30 cm was used to measure the depth of the soil layer.

Cylindrical samplers were hammered into the soil using a flat piece of wood facing down vertically to make sure the cylindrical sampler enters the soil evenly. Then the cylindrical sampler was carefully removed by digging it out and the soil was put into the bag. This known volume of soils allowed for determination of soil bulk density after drying and weighing.

The same sample was used for chemical analyses. All the three top soils from one sampling plot were placed in one bag and the other three sub-soils placed in another one bag. The bags were labelled top soil bag “H A” and sub-soil bag “H B”. Then soil samples were dried in the conventional oven at 105 ^{o}C for 48 hours and weighed afterwards. The soil samples were reduced in size by splitting into four quarters and throwing away two random quarters repeatedly leaving about 100 g that was put into bags and sent for laboratory analysis to determine soil type, texture, nutrient contents, water holding capacity, organic matter and soil pH. For recording forms see Appendix 4.

Top soil (Horizon A) Subsoil (Horizon B)

Figure 0.9: An example of a soil profile where soil samples were collected. (photo: F. Kayofa 2013)

3.5 Laboratory work

3.5.1 Taproot core samples

Core samples were grouped into four groups according to their taproot wet mass:

1st group	0 – 0.9 kg	2nd group	1 – 1.9 kg
3rd group	2 – 3.9 kg	4th group	4 kg and more.

The samples were dried in the oven at 60 ^{0}C for 24 hours and weighed for their dry mass. Each core sample was cut into small pieces of about 2 mm using a pair of secateurs. All the core pieces were milled into powder using the Retsch Z200 machine through 0.5 mesh at 8000 rpm. Milled core pieces were sifted into a shaker machine M200 for 5 minutes through 600, 425, 250 and less than 250 µm sieves (Figure 3.10). The milled core pieces were sifted through different sieve sizes (µm) to separate fine powder from coarse powder and find which powder can be analysed. Then core powder was placed into micro-columns of <250, 250, and 425 - 600 µm as per their sizes. All the micro-columns were labelled <250, 250, and 425 – 600 and their mass were recorded. Appendix 8 presents analysis results of sugar and starch contents.

Cores on scale Core pieces Shaker machine Retsch machine Sieves

Figure 0.10: Equipment used to mill core samples into powder (photo: F. Kayofa 2014).

3.5.2 Analysis of non-structural carbohydrates (NSC)

Carbohydrates consists of single molecules of glucose, galactose and fructose, and double molecules of sucrose and other chains of many molecules as well as starch which is made up of many glucose molecules. These sugar molecules are extracted using different methodologies, (Nielsen, 1998). The method of determining carbohydrate content by calculating the percent of carbohydrates remaining after all other components such as moisture, protein, lipid and minerals had been extracted leads to erroneous results because of experimental errors, (Nielsen, 1998).

3.5.3 Methods of carbohydrates isolation techniques

The sample is dried under vacuum to prevent thermal degradation, ground to a powder to increase solvent extraction then defatted by solvent extraction. The defatted sample is boiled with 80% alcohol solution because low molecule sugars are soluble in alcohol solution. The soluble components are separated from insoluble components by filtering the boiled solution. Then the filtrate and retentant are collected, dried and weighed to determine their concentration, (Nielsen, 1998). Some of the other small molecules that might be present in the extracts can be removed by treating the solution with clarifying agents or by passing the solution through one or more ion-exchange resins, (Nielsen, 1998).

3.5.4 Chromatographic and electrophoretic methods

These methods are used to separate and identify carbohydrates, whereby carbohydrates are separated based on their differential adsorption characteristics by passing the solution through a column. Carbohydrates can also be separated by electrophoresis after they have been derivitised to electrically charge them (Nielsen, 1998).

3.5.5. Enzymatic methods

Enzymes are added to the samples. These enzymes have the capacity to catalyse specific reactions and are rapid, highly specific and sensitive to low concentration. Amyloglucosidase is used to convert starch into glucose. Sucrose is converted to glucose with invertase while fructose is converted to glucose with phosphoglucose isomerase (Liu and Tyree, 1997). Liquid samples can be tested directly but solid samples should be dissolved in water first (Nielsen, (1998).

3.5.6 Analysis of non-structural carbohydrate (NSC) storage (sugar contents)

3.5.6.1 Extraction of glucose and fructose

The core powder samples were taken to Horticulture Laboratory in Stellenbosch University for analysis. Only milled core samples of <250 µm were measured and used to analyse non-structural carbohydrates. The laboratory used Micro Bio-spin™ P-30 gel columns to separate the sugar and starch fractions. 50 mg of sample was placed into each micro-column and 4 ml of 80 % ethanol was added. Micro-columns were put in a large heater at 80 ^{o}C for 30 minutes (Figure 3.11 A). Then micro-columns were centrifuged for 7 minutes at a speed of 4000 rpm (Figure 3.11 B).

After centrifuging, the sample residues settled at the bottom of each micro-column and ethanol with sugars at the top of the micro-column. The top part, a clear liquid, was transferred to a bottle for further analysis. All the ethanol extracts were transferred to one bottle containing 10 ml after a total of four extracts. The extraction steps were thus repeated four times but applying 2 ml of 80 % ethanol in the second, third and fourth extract. The micro-columns stayed in a large heater for 30 minutes for the first extract and 15 minutes for the second, third and fourth extracts. The 80 % ethanol was used to extract a particular carbohydrate fraction that includes small carbohydrates such as monomers, dimers and oligosaccharides (*i.e.* a small number of simple sugars (monosaccharides)) (E. A. Rohwer, personal communication, April 14, 2014).

3.5.6.2 Extraction for long chain glucose

Long chain sugars are extracted with water, whereby 4 ml of water is put into each micro-column with the residuals used in the extraction of simple sugars (section 3.5.2.1). Micro-columns were put in the oven at 80 ^{o}C for 23 hrs. Then micro-columns were taken to the centrifuge for 7 minutes at a speed of 4000 rpm to get a clear liquid extract (Figure 3.11 (B)). After centrifuging, the sample residues settle at the bottom of the micro-columns and water with sugars at the top of the micro-columns. The top part, clear liquid transferred into a bottle for further analysis. These same steps are repeated three times.

The fourth time 4 ml of water was added to the micro-columns with residues from the third time of extraction and left in the oven at 80 ^{o}C for 19 hours, then centrifuged for 7 minutes at a speed of 4000 rpm to get clear liquid. The clear liquid was again transferred to the same bottles of the first three extracts and then contained 16 ml of water extract. The water extraction was to extract water soluble carbohydrates which can be referred to as the polysaccharides (long chains of sugars (monosaccharides)) which were not already extracted during 80 % ethanol extraction ((E. A. Rohwer, personal communication, April 14, 2014).

3.5.6.3 Starch extraction

After water extraction, the residues left behind at the bottom of each micro-column then contained starch (long complex chains of simple sugars (monosaccharides)) and other compounds such as cellulose and lignin.

Two ml of water was added to each of the micro-columns and they were placed in a large heater at 100 ^{o}C for an hour to cook the residues and loosen the starch. The starch in the residues was then hydrolysed enzymatically to glucose by adding two ml of an enzyme-water mixture to the micro-columns totalling volume to 4 ml (E. A. Rohwer, personal communication, April 14, 2014).

The sample was left in the oven for the night at 60 ^{o}C for the enzyme to break all the starch-molecules into single, loose glucose-sugars. Then the glucose from the starch hydrolysis was measured on the HPLC (High-performance Liquid Chromatography) by separating sugars in the mixture as well as identifying and quantifying each sugar (Figure 3.11 D).

The total sugars extracted in the 80 % ethanol and water fractions were analysed in the spectrophotometer by the phenol sulfuric acid assay using glucose as a standard (Figure 3.11 C) (E. A. Rohwer, personal communication, April 14, 2014).

Large Heater (A) Centrifuge (B) Spectrophotometer (C) HPLC (D)

Figure 0.11: Equipment used for the analysis of non-structural carbohydrates in taproot core samples (photo: F. Kayofa 2014).

The concentration of different sugars (oligosaccharides, polysaccharides and starch) were converted into sugar contents using the below equations**:**

Equation 3: Oligosaccharides content

Oligosaccharides content = taproot mass x oligosaccharides concentration x 1000 / 100 (g)

Equation 4: Polysaccharides content

Polysaccharides content = taproot mass x polysaccharides concentration x 1000 / 100 (g)

Equation 5: Starch content

Starch content = taproot mass x starch concentration x 1000 / 100 (g)

3.5.7 Soil analysis

3.5.7.1 Extraction of pH, base cations and organic carbon

Soil samples collected were taken to Bemlab commercial laboratories to analyse soil nutrient contents, textures, water holding capacity and pH as they influence the regeneration of *Pterocarpus angolensis*. The soil was air dried and sieved through a 2 mm sieve to determine stone fraction (mass/mass basis).

Walkley-Black method was used to analyse organic matter (The Non-affiliated Soil Analyses Work Committee, 1990). Soil pH was measured in a 1.0 M KCL solution using a soil solution ratio of 1:2.5. Extractable cations such as K, Ca, Mg and Na were extracted at pH =7 with 0.2 M ammonium acetate. Micro-nutrients; Zn, Mn, Cu, and Fe were extracted with Diammonium EDTA (0.02 M) while Boron (B) by using 1.2 hot water ratio (The Non-affiliated Soil Analyses Work Committee, 1990). A Varian ICP OES optical emission spectrometer was used to analyse the extracted solutions. Extractable acidity was extracted with 1M KCL and determined through titration with 0.05 M NaOH (The Non-affiliated Soil Analyses Work Committee, 1990).

3.5.7.2 Extraction of P

A method adapted from that described by Nelson and Sommers (1996) was used to determine the total P in the soil. The P was extracted from soil through acid digestion using a 1:1 mixture of 1 N nitric acid and hydrochloric acid at 80 ^{0}C for 30 minutes. The P concentration in the extract was then determined with a Varian ICP-OES optical emission spectrometer. Both total C and N content of soil were determined through total combustion using a Leco Truspec® CN N analyser.

3.5.7.3 Analysing of soil texture and water holding capacity

Chemical dispersion was done using sodium hexametaphosphate (calgon) and three sand fractions were determined through sieving as described in The Non-affiliated Soil Analyses Work Committee (1990). Silt and clay were then determined using sedimentation rates at 20 ^{o}C, using an ASTM E100 (152H-TP) hydrometer. The soil water holding capacity was then determined mathematically from the soil texture using a calculation model adapted from that of Saxton *et al.* (1986).

The soil contents were calculated as follow:

Equation 6: ECEC

$ECEC = \sum basic\ cations + Acid\ cation\ (H^{+})$ $(cmol_c\ kg^{-1})$

Equation 7: Acid Saturation

Acid saturation $= \frac{\text{Acid cation}}{\text{ECEC}}\ x\ 100$ (%)

Equation 8: Sum of basic cations

Sum of basic cations = Na + K + Ca + Mg $(cmol_c\ kg^{-1})$

3.5.8 Analysis of tree growth ring cross-dating

The cross-section surface of taproot necks were manually sanded to a highly polished surface using progressively finer textures of sand papers in sequence, namely 60, 80, 100, 120, 180 and 200 grit (Figure 3.12 A & B). Growth rings of some necks were invisible with naked eye. Hence, lower magnification microscope was used to easily identify growth rings due to their discontinuous formation of large vessels in the early wood and presence of small vessels at the late wood (Stahle, 1999). The Lintab tree ring measuring system was used for cross dating and measuring tree growth rings (Figure 3.12 C). The specimen was placed on the sample support table to scan the specimen surface through microscope. Measuring of growth rings was done at length unit of 1/100 mm and the measuring movement of the specimen was from left to right i.e. from bark to pith. Growth rings were measured from two radii of each specimen, then averaged.

Taproot neck discs (A) Sand papers (B) Lintab tree ring measuring system (C)

Figure 0.12. (A), (B) &(C): Materials and equipment used for growth rings counting and measurements (photo: F. Kayofa 2014).

3.6 Statistical Analysis

Statistica software was used to analyse the data because it produces clear and quality graphs for interpretation. The two-way factorial ANOVA (analysis of variances) test and multiple comparison test performed to test differences among means of above (shoot mass) and below biomass (taproot mass), taproot depth and diameter, shoot mass and height, between two fire history treatments (recently burnt (RB)) and (recently unburnt (RU)) and between the three study locations (Okongo, Ncumcara and Caprivi). Simple linear regressions were performed to find the relationship between aboveground biomass and belowground biomass while multiple linear regressions were used to determine the effects of non-structural carbohydrates (NSC) on aboveground biomass, belowground biomass and shoot height. Histogram and normal probability: residual plots methods were used to test for normality assumption while Levene's test method used to test for homoscedasticity assumption and observed that some of the data variable were not normal distributed and homoscedasticity is not valid. Then a log transformation was performed to obtain normal distribution of the data set prior to analysis.

The log transformation was performed by calculating:

Equation 9: Log transformation

$$\textit{Logarithmic equation} = \textit{Ln}\ (x)$$

Chapter 4: Results

4.1 Introduction

This chapter provides the results of the data collected on *Pterocarpus angolensis* trees in the three study locations. These data includes information obtained from (a) interviews with people living in close proximity to the study sites, (b) field sampling plots collected from *Pterocarpus angolensis* tree populations, and (c) destructive samples of below-ground (taproot) and above-ground (shoot) biomass as well as non-structural carbohydrate (NSC) storage in the taproots. A schematic layout of these data sets are shown in Table 4.1.

Table 0.2: Overview of the data sets collected and presented in this thesis

Data type	Data set	Details	Section
Survey	Questionnaire data	Tree development stages Estimation of tree age Factors influencing tree growth Fire effects Environmental disturbances Tree resistant and vulnerable Tree management	4.2.4 4.2.8 4.2.9 4.2.10 4.2.11 4.2.13 4.2.14
Descriptive	Site data	Soil description and analysis Climate	4.3 Presented in 3.3.3
Stand data	Population data set	*Pterocarpus angolensis* size structure Stocking Tree stage BA & DBH Sapling analysis Bole tree analysis	4.4 4.5 4.6 4.6.1 4.6.2
Tree development stages	Destructive samples of **seedlings**	Tree developmental stages: destructive analysis Taproot parameters data Shoot parameters data Relationship between taproot variables Relationship between taproot and shoot variables	4.7 4.7.1.1 4.7.1.2 4.7.1.3 4.7.1.4
	Non-structural carbohydrates in **seedlings**	Storage in Taproots Relationship between taproot size and non-structural carbohydrates contents Tree growth rings in neck samples	 4.7.1.6 4.7.1.7
	Destructive samples of **saplings**	Taproot parameters data Shoot parameters data Relationship between taproot variables Relationship between taproot mass and shoot variables	4.7.2.1 4.7.2.2 4.7.2.4 4.7.2.5
	Non-structural carbohydrates in **saplings**	storage compounds in taproots Relationship between taproot mass and non-structural carbohydrates Relationship between shoot mass and non-structural carbohydrates Tree growth rings in neck samples	 4.7.2.6 4.7.2.7 4.7.2.8
Descriptive	Site data	Tree damage and stand disturbances	4.8

4.2 Questionnaire survey among forest users

4.2.1 Respondents age group and gender

During the interview 20 people from Okongo Community Forest and Caprivi State Forest as well as 16 people from Ncumcara Community Forest, ranging in age from less than 30 to more than 50 years old, were interviewed according to methods set out in section 3.3.1.4. The respondent's age and gender distribution percentage is shown in Figure 4.1.

The bulk of the respondents were older than 30 years old with age classes 30 – 50 and more than 50 fairly evenly represented. More males were interviewed compared to females in the age of 30 – 50 years old. At Okongo there were no people of less than 30 years old interviewed. Overall a high number of respondents are 30 – 50 years of age.

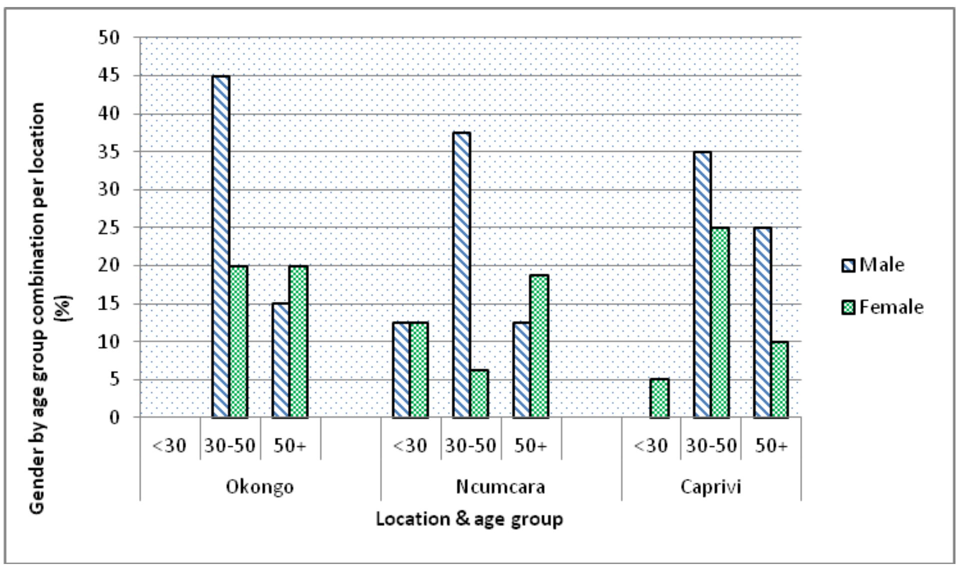


Figure 0.13: Respondents to questionnaires as per age group and gender.

4.2.2 Respondents age group and occupation

The respondents had occupations that included farmers, village heads, forestry officers, forest management committee members and carpenters. Farmers represent the highest percentages (34 %) of respondents interviewed. At Okongo and Caprivi many of the farmers are in the 30 – 50 year age group while at Ncumcara most of the farmers are in 50 + year age group. Most of the farmers interviewed were at Okongo. All the forestry officers interviewed were between 30 and 50 years old. The carpenters interviewed were only from Okongo and Caprivi (Figure 4.2).

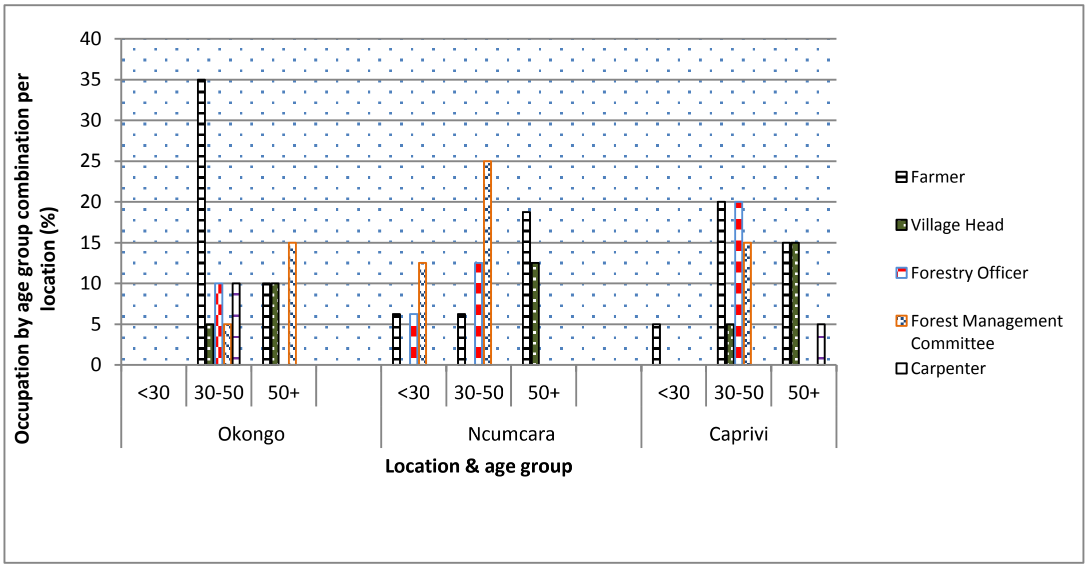


Figure 0.14: Respondents to questionnaires as per age group and occupation.

4.2.3 Rating of *Pterocarpus angolensis* seedlings, saplings and mature trees in the study locations

The frequency of occurrence of seedlings, saplings and mature trees in each location were rated as unknown, sparse, average and abundant. At Okongo most of the respondents rated seedlings as average while saplings and mature trees were mainly rated as abundant.

At Ncumcara no respondent rated mature trees as sparse and both seedlings and saplings were rated as abundant. Caprivi had the highest percentages of respondents that rated seedlings as sparse. The stages rated most abundant per location are mature trees at Okongo and saplings at both Ncumcara and Caprivi. Figure 4.3 indicates respondent's ratings of the presence of *Pterocarpus angolensis* in the three locations.

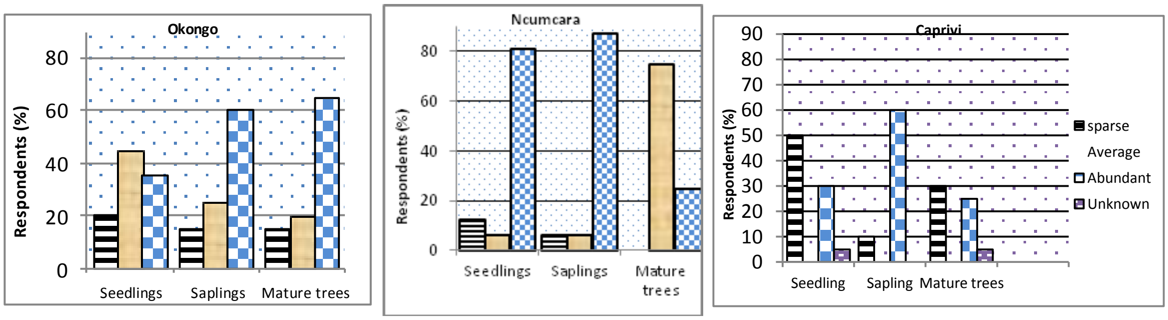


Figure 0.15: Respondents' rating of *Pterocarpus angolensis* seedlings, saplings and mature tree presence in three study locations.

4.2.4 Different stages of *Pterocarpus angolensis* development

This question was open-ended in the questionnaires that were used (Appendix 1). The main *Pterocarpus angolensis* development stages mentioned by the respondents were shrubs, small, medium, big, pole, timber, seedlings, sapling and mature trees. Similar stage names were combined in one name and as a result only seedling, sapling and mature tree development stages are presented in Table 4.2. "Small" was regarded as similar to seedling, "shrubs", "medium" and "poles" as similar to sapling and "big" and "timber" as synonyms for the mature tree stage. At Okongo and Caprivi, few of the respondents referred to seedling stages as compared to other stages.

Table 0.3: Percentage of respondents familiar with specific developmental stages of *Pterocarpus angolensis*

	Okongo	**Ncumcara**	**Caprivi**
Stages	**Respondents (%)**	**Respondents (%)**	**Respondents (%)**
Seedlings	60	96	70
Saplings	95	88	90
Mature tree	90	88	90
Unknown	0	13	10

4.2.5 *Pterocarpus angolensis* germination in the forest

A total of 85% of the respondents from Okongo, 56 % from Ncumcara and 75 % from Caprivi indicated that they know how *Pterocarpus angolensis* germinates in the forest. According to respondents, tree germinates after burning (Okongo 29 %, Ncumcara 6 %, Caprivi 15 % of the respondents) and also during rainfall (Okongo 93 %, Ncumcara 31 %, Caprivi 25 % of the respondents). Between 12 % and 20 % of respondents at Ncumcara and Caprivi indicated that after fire and rainfall the single shoot germinates first from the seed (Table 4.3).

Table 0.4: Respondents expressed their views on the germination of *Pterocarpus angolensis* tree in the forest and their explanation on how the tree germinates.

	Okongo		Ncumcara		Caprivi	
	Respondent (%)		Respondent (%)		Respondent (%)	
Question	Yes	No	Yes	No	Yes	No
Knowledge on Pterocarpus angolensis germination in the forest	70	30	56	44	65	35
Germinate after burning	29		6		15	
Germinate during rainfall	93		31		25	
Single shoot germinate first	0		6		15	
Germinate from seeds	0		13		20	

4.2.6 The time *Pterocarpus angolensis* seedlings take to reach the sapling stage

Estimates of time taken for seedlings to progress to the sapling stage are presented in Table 4.4. The majority of the respondents at Okongo and Ncumcara suggested seedling takes 4 – 7 years to reach sapling stage while the highest percentages of Caprivi respondents indicated seedling takes 2 years. Only few respondents of Okongo and Caprivi suggested seedling takes 16 – 25 years. At Okongo and Ncumcara there were no respondents who perceived that seedlings can develop to the sapling stage in one year (Table 4.4).

Table 0.5: Estimates of respondents on the time taken by seedlings to reach the sapling stage.

Time taken to reach sapling stage (Years)	**Okongo**	**Ncumcara**	**Caprivi**
	Respondents (%)	**Respondents (%)**	**Respondents (%)**
1	0	0	15
2	5	6	20
3	12	6	10
4 - 7	23	62	10
8 - 15	10	6	10
16 - 25	5	0	5
Unknown	45	20	30

4.2.7 *Pterocarpus angolensis* advancement from seedling stage to the bole tree stage in the forest

A total of 80% of the respondents in Okongo 43% in Ncumcara and 50% in Caprivi indicated to know how *Pterocarpus angolensis* advances from seedling stage to bole tree stage (Table 4.5). Based on the respondents, the tree generally grows fast from seedling to sapling but grows slowly from sapling to bole tree stage particularly in the absence of fires and when there is competition from other plants. The dominant developmental pattern described by most respondents is that the tree shoot initially grows straight up, and then starts to branch out while the stem thickens until the tree is about 100 years old.

Table 0.6: Respondents knowledge on the advancement of *Pterocarpus angolensis* from seedling stage to the bole tree stage in the forest.

	Okongo Respondents (%)		**Ncumcara Respondents (%)**		**Caprivi Respondents (%)**	
Question	Know	Not know	Know	Not know	Know	Not know
Knowledge on *Pterocarpus angolensis* advancement from seedling stage to the bole tree stage in the forest	80	20	44	56	50	50

4.2.8 Estimations of the number of years that *Pterocarpus angolensis* takes to advance from sapling to bole tree stage

When asked how long *Pterocarpus angolensis* takes to advance from sapling to the bole tree stage, the estimates of Okongo respondents covered all age classes with roughly equal frequency (Figure 4.4). In strong contrast, respondents at Ncumcara favoured the 5-10 year class while the Caprivi respondents favoured the > 20 years class. The median age class for the three locations were 10-15 (Okongo), 10-15 (Ncumcara) and 15-20 (Caprivi). The 10 % Okongo and 5 % Caprivi respondents were unable to estimate the time taken to advance from sapling to bole tree stage (Figure 4.4).

4.2.9 Edaphic and environmental factors influencing *Pterocarpus angolensis* development from saplings to bole tree stage

The majority of the respondents of all locations (Okongo, Ncumcara and Caprivi) alleged soil water as the main influential factor. Soil fertility was also perceived as the second most influential factor mainly by Okongo and Caprivi respondents. Other influential factors indicated are fires, sunlight and plant competition. The wind was also indicated by 10 % of Caprivi respondents. All the suggested influential factors are depicted on Figures 4.5 (A), (B) & (C).

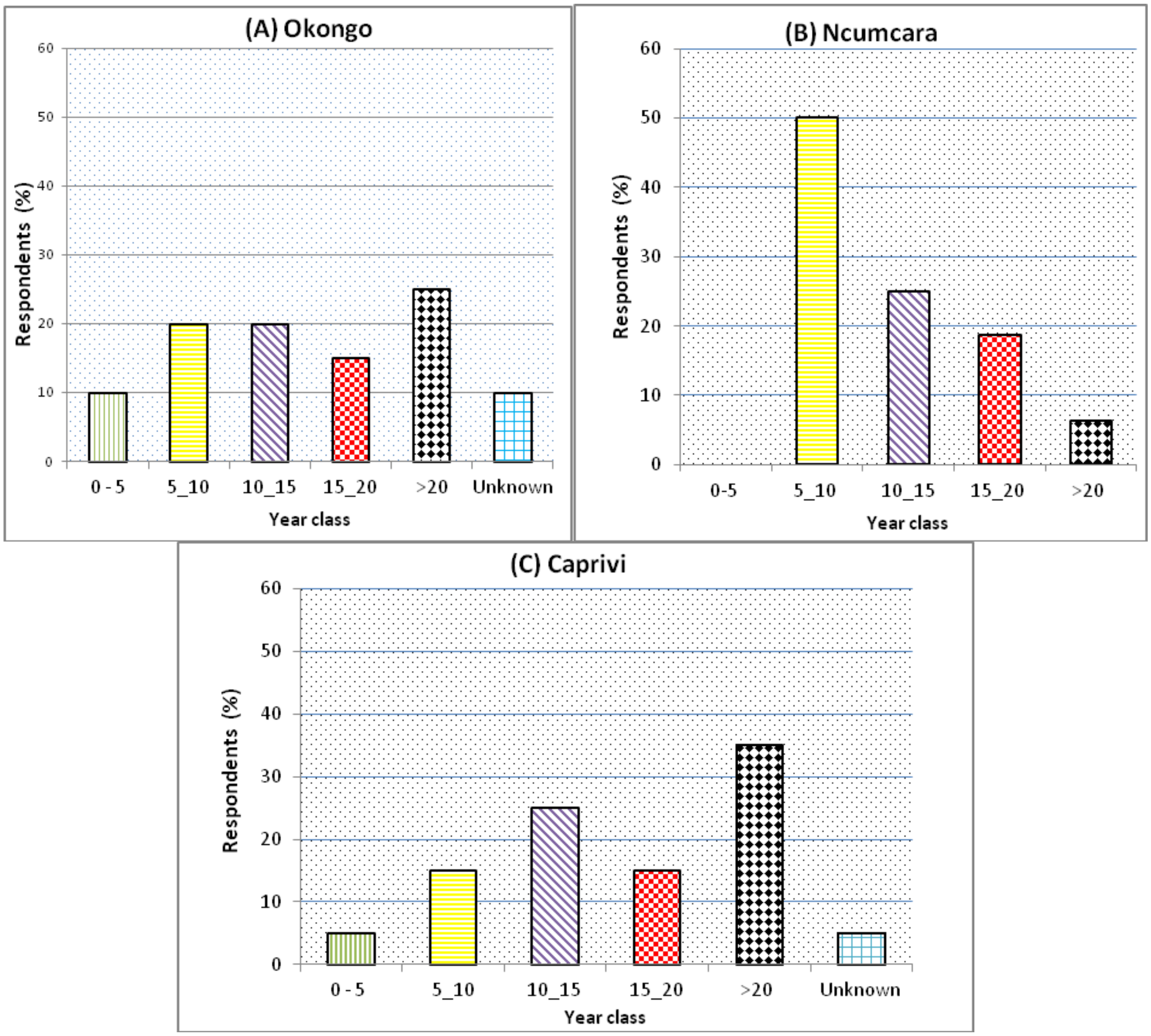


Figure 0.16 A, B & C: Estimation of time that *Pterocarpus angolensis* takes to advance from sapling to bole tree stage by members of communities adjacent to forests.

4.2.10 Management operations that affect *Pterocarpus angolensis* development from sapling to bole tree stage (Refer to Appendix 9).

4.2.10.1 The effect of the absence of fire during one fire season

The majority of the respondents (85 % Okongo, 87 % Ncumcara and 90 % Caprivi) purported that absence of fires during one fire season has a large effect on the development from sapling to bole tree stage. Only 10 % each from Ncumcara and Caprivi respondents indicated small effect while 5 % at Okongo and 13 % at Ncumcara indicated medium effects.

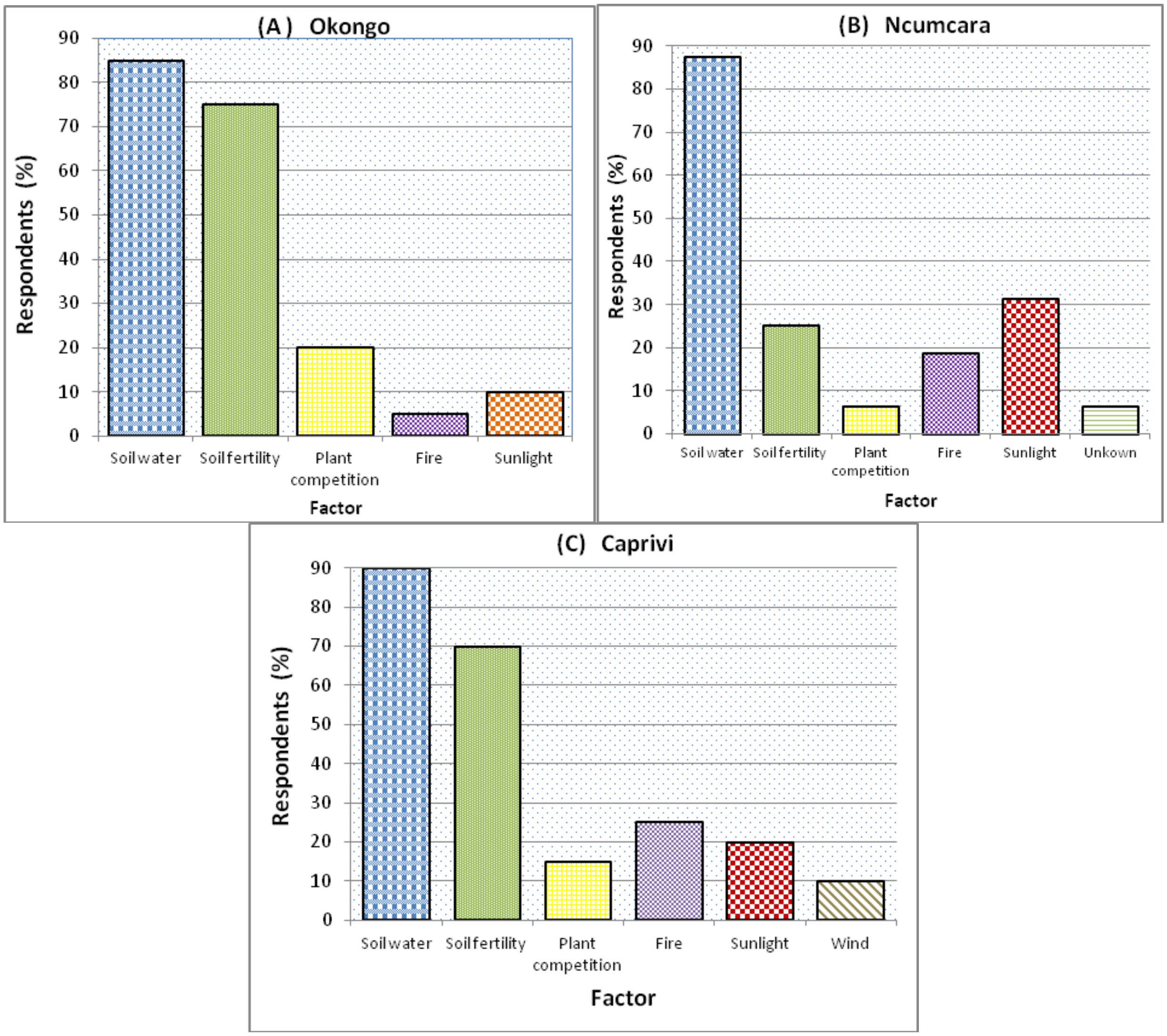


Figure 0.17(A), (B) & (C): Perceived edaphic and environmental factors influencing *Pterocarpus angolensis* development from saplings to bole tree stage by members of surrounding communities.

4.2.10.2 The effect of the absence (or low levels of) of domestic livestock

The majority of the respondents suggested domestic livestock has large effect, namely in Okongo 40 %, Ncumcara 69 % and Caprivi 90 %. Some respondents (40 % Okongo, and 25 % Ncumcara) alleged domestic livestock has no effect. 5 % each of Okongo and Caprivi indicated small effect and medium effect. The other respondents (10 % Okongo and 6 % Ncumcara) indicated not knowing any effect of domestic livestock.

4.2.10.3 The effect of the absence (or low levels of) game animals that browse the trees

A large number of respondents (Okongo 60 %, Ncumcara 69 % and Caprivi 90 %) perceived absence of game animals have large effect. However, 25 % at Okongo, 25 % at Ncumcara and 5 % at Caprivi indicated that it does not have an effect. Only 5 % of Okongo indicated small effect while 5 % at Okongo, 6 % at Ncumcara and 5 % at Caprivi suggested medium effects. The 5 % of Okongo respondents indicated not knowing the effect of game animals.

4.2.10.4 The effect of vegetation management in the neighbourhood of the tree

High percentages of respondents (Okongo 100 %, Ncumcara 88 % and Caprivi 90 %) purported large effect of partial removal of competing vegetation. The remainder of respondents (13 % Ncumcara and 10 % Caprivi) indicated medium effect.

4.2.10.5 The effect of higher than average rainfall in a particular year

The respondents 70 % Okongo, 88 % Ncumcara and 85 % Caprivi maintained that higher than average rainfall has large effect but only 5 % Okongo, 6 % Ncumcara and 10 % Caprivi indicated medium effect. The other 5 % Okongo, 6 % Ncumcara and 5 % Caprivi suspected small effect while 5 % Okongo indicated no effect. Caprivi 10 % respondents indicated not knowing the effect of higher than average rainfall.

4.2.10.6 Other management operations

Respondents again indicated that other management operations affecting *Pterocarpus angolensis* development from sapling to bole tree stage are soil conditions (soil fertility) and temperature such as frost that kills susceptible seedlings and saplings.

4.2.11 Environmental disturbances that affect *Pterocarpus angolensis* development from saplings to bole tree stage

Respondents suggested that the most influential environmental disturbance is fire: Okongo 40 %, Ncumcara 92 % and Caprivi 70 %. One non-environmental disturbance highlighted by the respondents is human beings cutting that includes small poles to big trees to use for homestead construction, wood carving and planks perceived by 88 % of Ncumcara respondents. Caprivi respondents of 15 % indicated not knowing environmental disturbances (Figure 4.6).

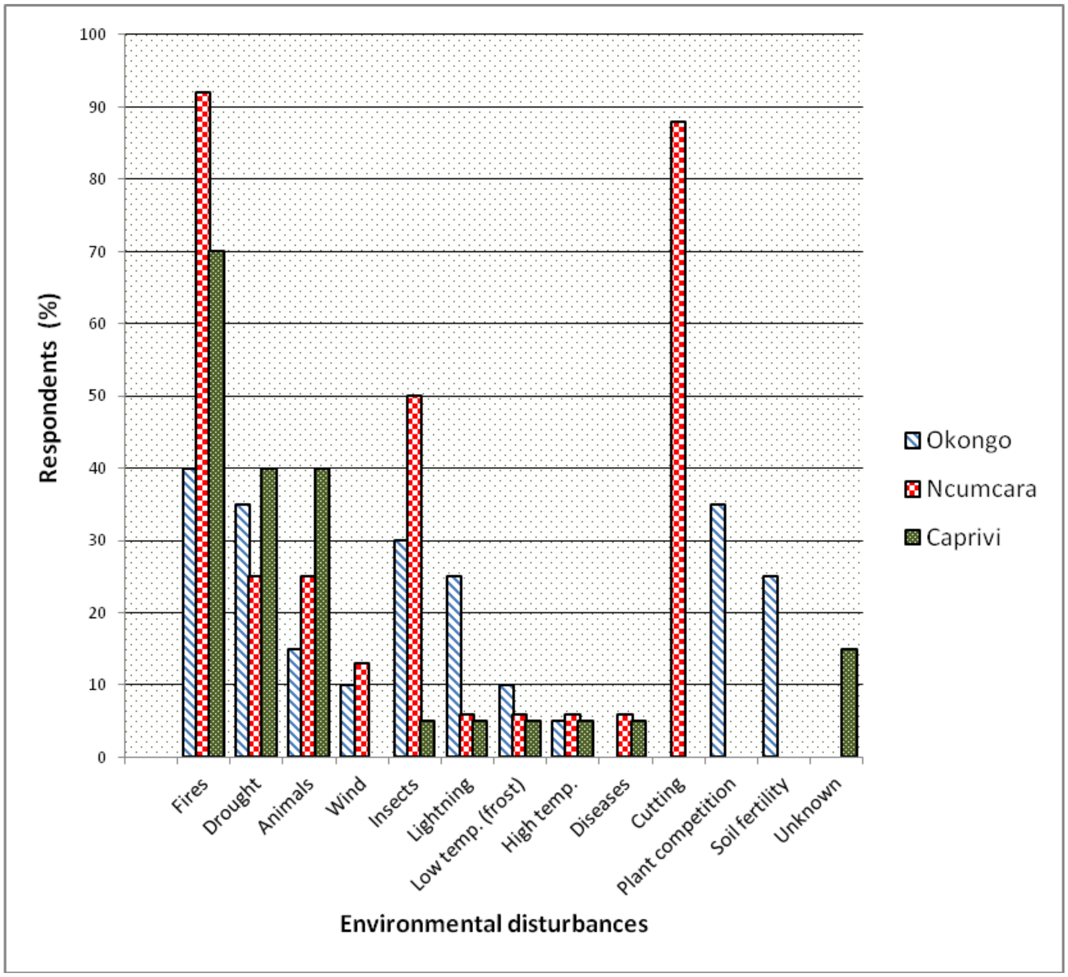


Figure 0.18: Environmental disturbances that affect *Pterocarpus angolensis* development from saplings to bole tree stage

4.2.12 Fire occurrence in the study locations

A high number of respondents indicated that fire effectively occurs every year in each of the three locations, especially when the rainfall in a preceding rainy season is at normal or above normal, the fractions being Okongo 75 %, Ncumcara 94 % and Caprivi 100 %. At Ncumcara, 6 % of respondents indicated the fire occurs every two years while 20 % of Okongo respondents indicated that some part of Okongo community forest were not burnt for the last 5 – 20 years (Figure 4.7).

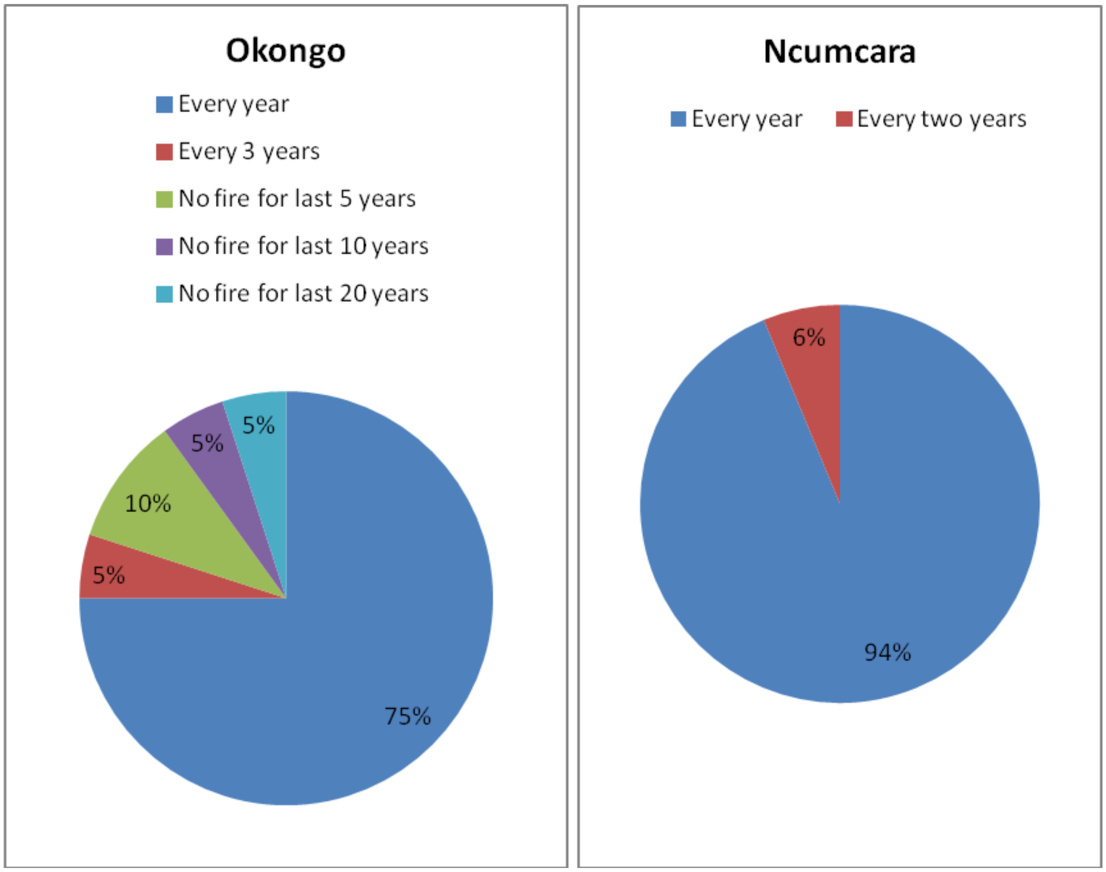


Figure 0.19: Perceptions of respondents about fire occurrences in the two study locations. Take note Caprivi respondents not included in the graph because all the respondents indicated that fire occurs every year.

4.2.13 *Pterocarpus angolensis* development stages that are resistant and those vulnerable to fires

The bole tree stage is regarded as resistant by many respondents (Okongo 85 %, Ncumcara 100 % and Caprivi 95 %). Sapling stage was also perceived as resistant (Okongo 80 %, Ncumcara 81 % and Caprivi 85 %). The majority of respondents ranging from 95 % to 100 % indicated that seedling stage is vulnerable to fires. Some respondents from 10 – 20 % of all three locations proposed saplings are vulnerable, especially when the fire intensity is high or when crown fires occur. While 15 % respondents each from Okongo and Caprivi indicated bole tree stage vulnerable especially when the tree has thick dry bark and dry spots on the stem. The 5 % of Caprivi respondents indicated that they do not know which stages trees are resistant or vulnerable. Figure 4.8 indicates the perceived fire resistance or vulnerability of tree growth stages.

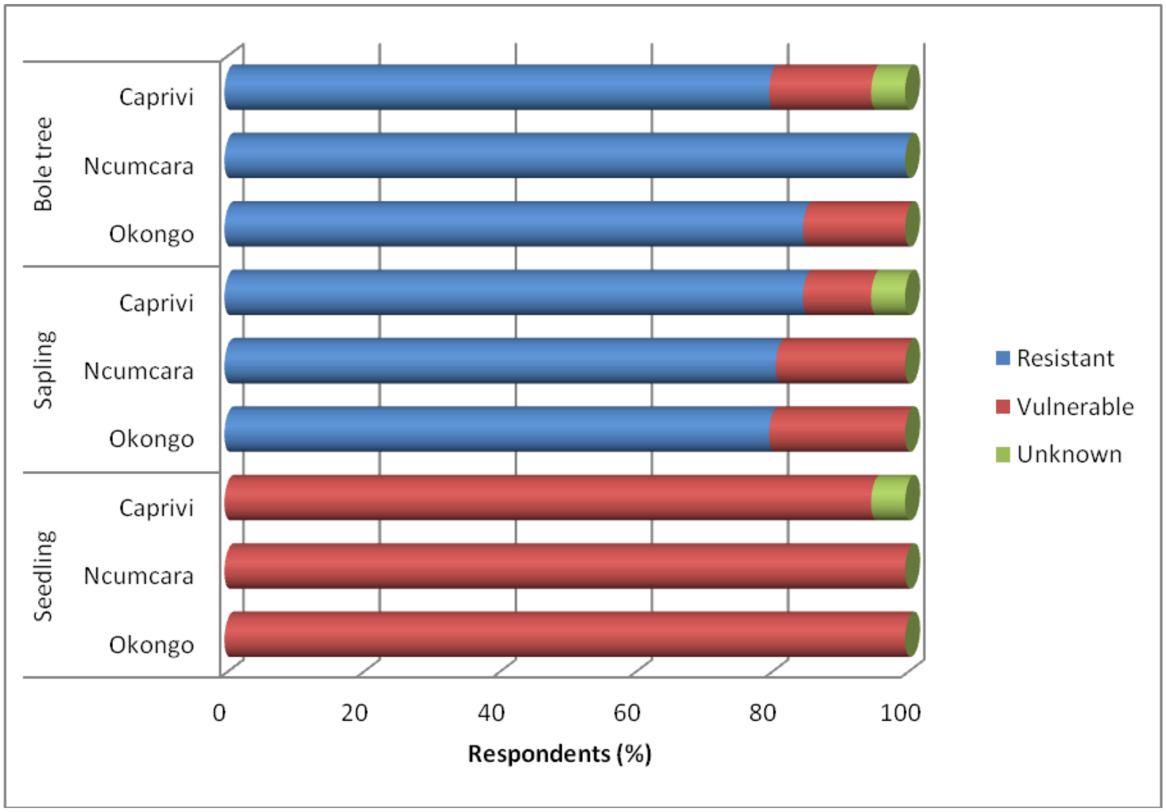


Figure 0.20: *Pterocarpus angolensis* development stages that are perceived to be resistant or vulnerable to fires.

4.2.14 Silvicultural practices being performed by the community to promote *Pterocarpus angolensis* growth

A high percentage of respondents stated that there are no silvicultural practices performed to promote *Pterocarpus angolensis* growth (Okongo 95 %, Ncumcara 63 % and Caprivi 100 %). There are only 5 % of Okongo and 38 % of Ncumcara respondents indicated some silvicultural practices being practiced by the community. The practices highlighted by respondents are thinning, pruning and selective harvesting. Caprivi respondents indicated no silvicultural practices being performed (Table 4.6).

Table 0.7: Respondents views on silvicultural practices performed by communities adjacent to forests.

Question	Okongo Respondents (%)		Ncumcara Respondents (%)		Caprivi Respondents (%)	
	Yes	No	Yes	No	Yes	No
Does the community perform some silvicultural practices to promote *Pterocarpus angolensis* growth?	5	95	38	62	0	100

4.3 Soil description and analysis

These soil characteristics in this section are there to provide background on the edaphic conditions that the trees experience across the three locations studied. No statistical tests are provided for the soil data because the fire history treatments were actually selected with the aim of having quite similar soil conditions on all three locations.

Soil analysis results confirmed that the soil texture at all the three locations is dominated by sand. The pH KCl ranges from 4.9 to 5.3, phosphorus 8.5 to 12 mg/kg, organic carbon 0.19 to 0.39 % and water holding capacity 57 to 89 mm/m (Table 4.7). Soil properties could not be statistically analysed because the aim was only to confirm with the information on soil characteristics of Miombo woodland that are already in the literature.

Table 0.8: Soil characteristics of the three study locations and fire history (recently burnt, RB or recently unburnt, RU).

Location	Fire	Soil texture	Horizon	pH	H^+	P: Bray II	Sum (+)	ECEC	Acid saturation	C	Water holding capacity
				(1M KCl)	($cmol_c$ kg^{-1})	(mg/kg)	($cmol_c$ kg^{-1})	($cmol_c$ kg^{-1})	%	%	mm/m
Okongo	RB	Sand	A	4.9	0.5	8.5	1.24	1.70	29.8	0.20	84
Okongo	RU	Sand	A	4.2	0.59	9.5	0.73	1.32	44.27	0.22	81
Ncumcara	RB	Sand	A	4.6	0.5	9.25	0.95	1.45	34.40	0.24	57
Ncumcara	RU	Sand	A	4.7	0.56	8.75	1.25	1.81	31.00	0.19	79
Caprivi	RB	Sand	A	5.4	0.38	12	1.75	2.13	18.47	0.39	89
Caprivi	RU	Sand	A	4.6	0.53	8.5	1.03	1.55	34.25	0.27	67

Figures 4.9 to 4.15 indicate the trends of Sum (+) and H^+ levels, water holding capacity, phosphorus, pH, acid saturation, ECEC and organic carbon contents in the three locations. The extractable acidity (H^+) varies between 0.4 and 0.6 $cmol_c\ kg^{-1}$ across all locations, the sum of base cations on the exchange takes up between 0.7 and 1.7 $cmol_c\ kg^{-1}$ (Figure 4.9). This means that all soils are strongly dystrophic (Soil classification working group, 1991), having base cation contents of much less than 5 $cmol_c\ kg^{-1}$.

The water holding capacity of the burning history treatments are fairly similar and vary from 57 to 89 mm per meter soil depth. The lower levels (such as Numcara RB and Caprivi RU) are typical of pure sands and the higher levels in the range lean towards values that can be expected in loamy sands (Figure 4.10).

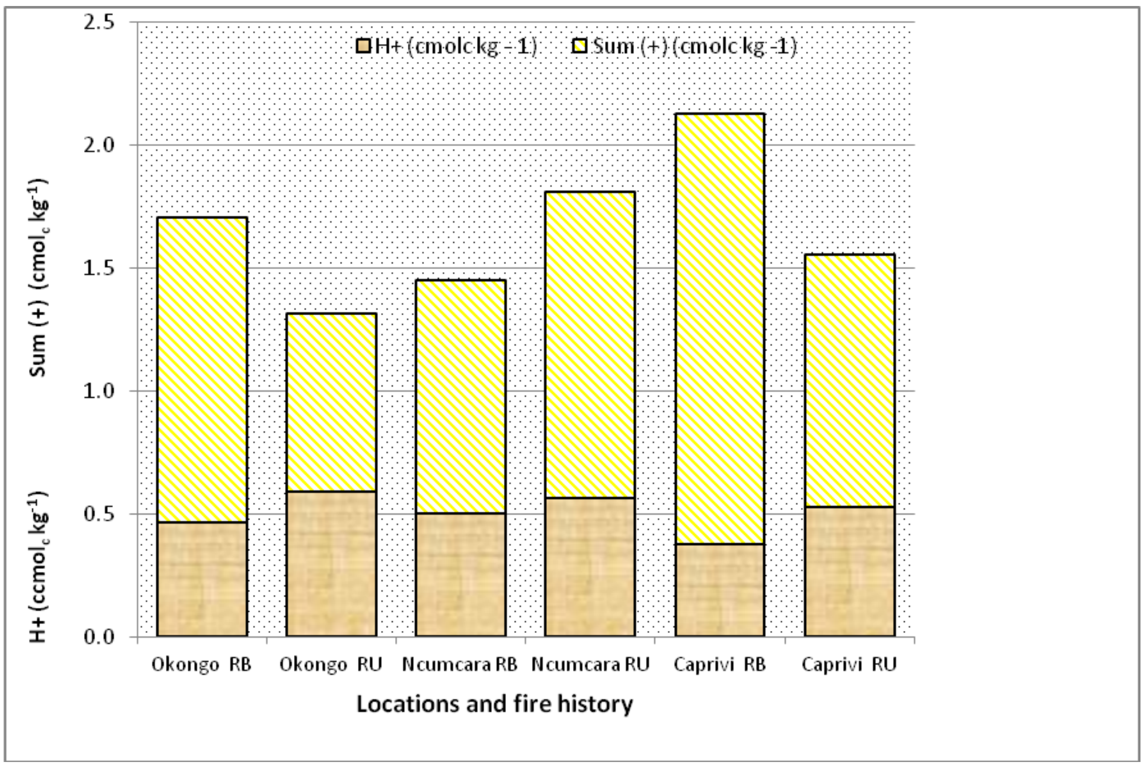


Figure 0.21: Sum of base cations and extractable acidity levels in the three locations (RB = Recently burnt, RU = Recently unburnt)

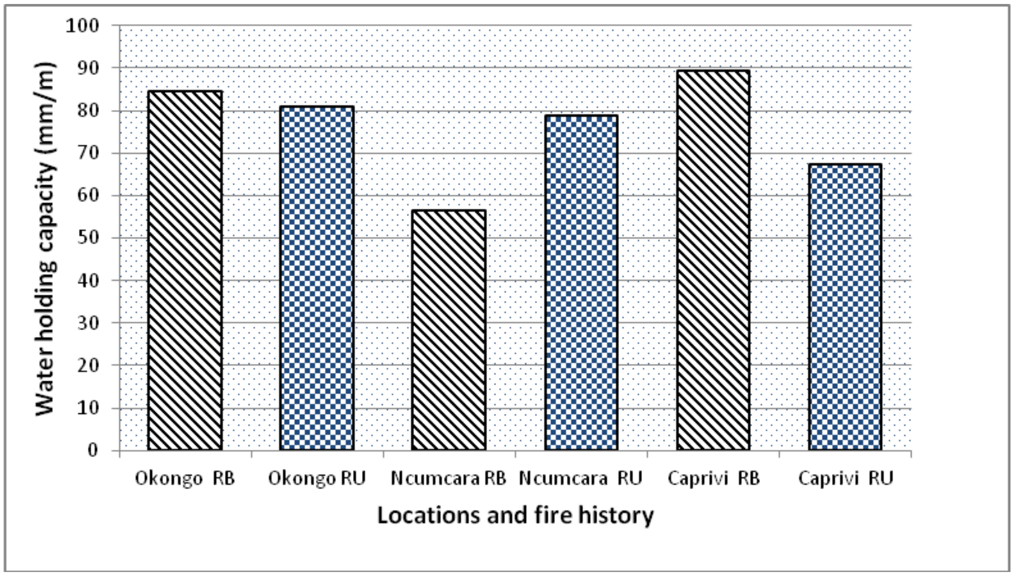


Figure 0.22: Water holding capacity per unit of soil depth in the three study locations (RB = Recently burnt, RU = Recently unburnt).

Caprivi recorded slightly higher phosphorus contents in recently burnt treatments while other fire history treatments in all the locations have more or less the same levels of phosphorus (Figure 4.11).

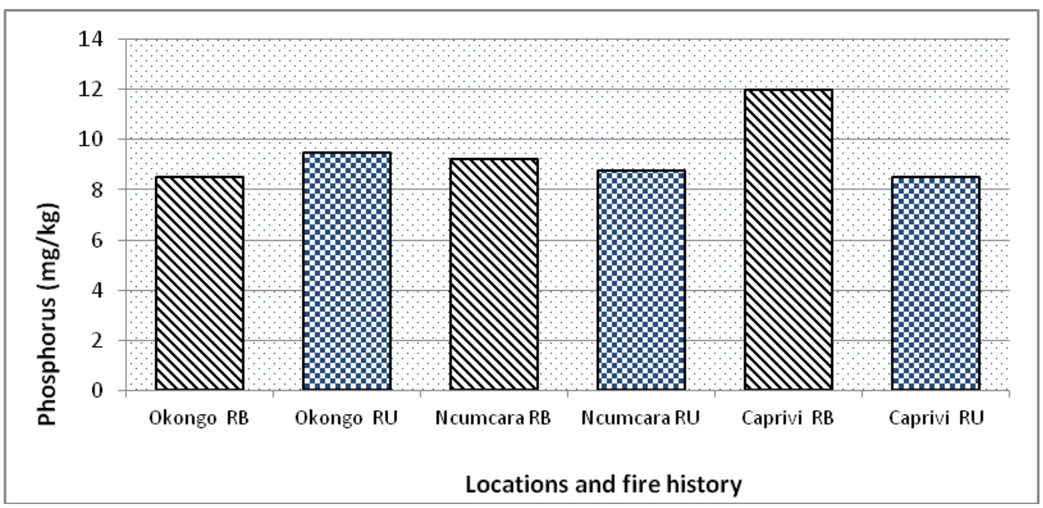


Figure 0.23: Phosphorus contents across locations and burning treatments.

The soil pH across all treatments and locations varied from 4.2 to 5.3 (Figure 4.12). The highest pH level (approximately 5) was noted in Caprivi and Okongo recently burnt treatments. The lowest pH, namely 4.2 was recorded in the recently unburnt treatments at Okongo (Figure 4.12).

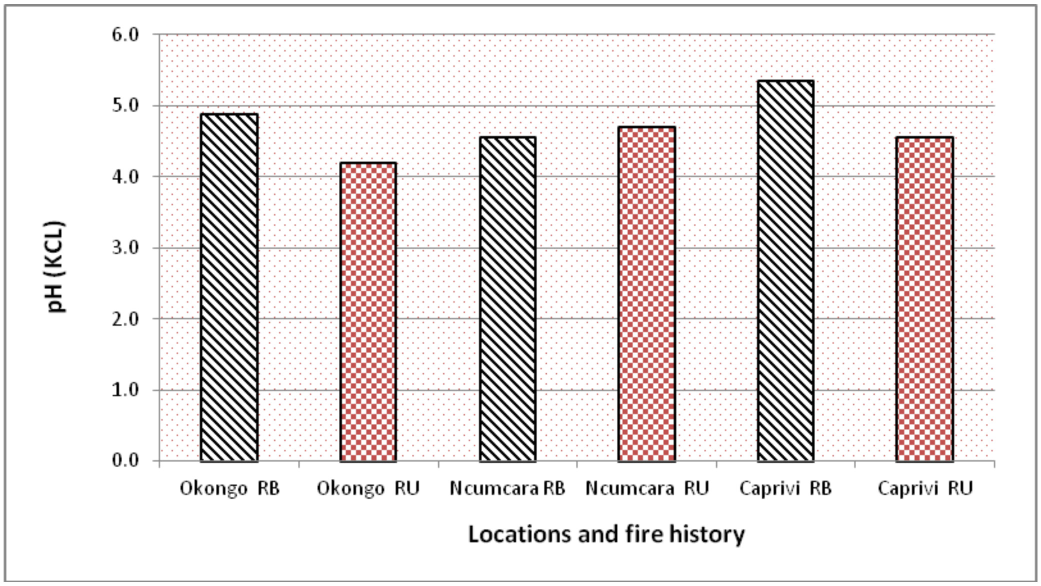


Figure 0.24: pH levels across locations and burning treatments (RB = Recently burnt, RU = Recently unburnt).

The Effective cation exchange capacity (ECEC) for the fire history treatments varied between 1.3 and 2.1 $cmol_c\ kg^{-1}$ which is very low (Figure 4.14). Caprivi has the highest ECEC in recently burnt treatments while Okongo has the lowest ECEC in recently unburnt treatments for all the locations. Both Okongo and Caprivi have the highest ECEC in recently burnt treatments and Ncumcara has the highest in recently unburnt treatments (Figure 4.13).

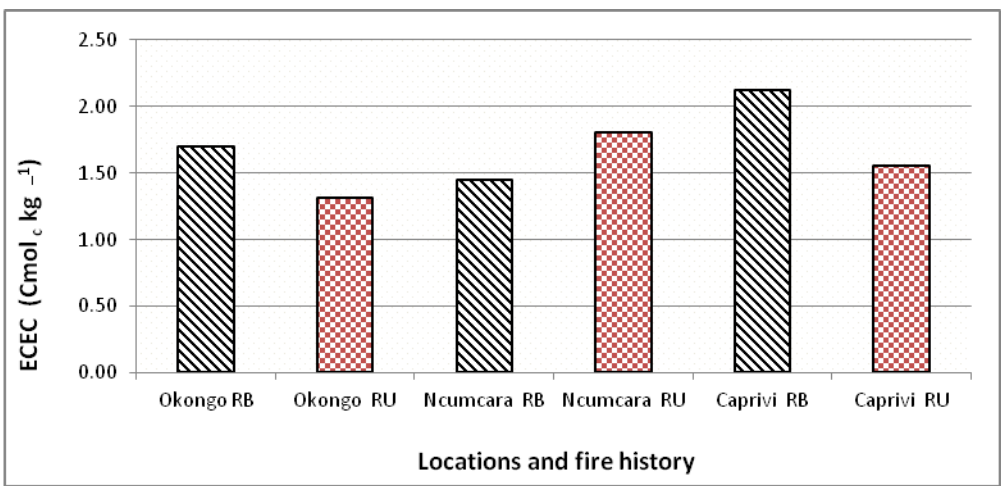


Figure 0.25: Effective Cation Exchangeable Capacity (ECEC) across locations and burning treatments (RB = Recently burnt, RU = Recently unburnt).

Acid saturation is the highest at Okongo recently unburnt treatments and lowest at Caprivi recently burnt treatments. At both Okongo and Caprivi the acid saturation is higher in recently unburnt treatments than in burnt treatments (Figure 4.14).

The topsoil organic carbon levels were highest at Caprivi recently burnt treatment (Figure 4.15). All other treatment x location combinations had similar levels of organic carbon, ranging from 0.18 to 0.26% (Figure 4.15).

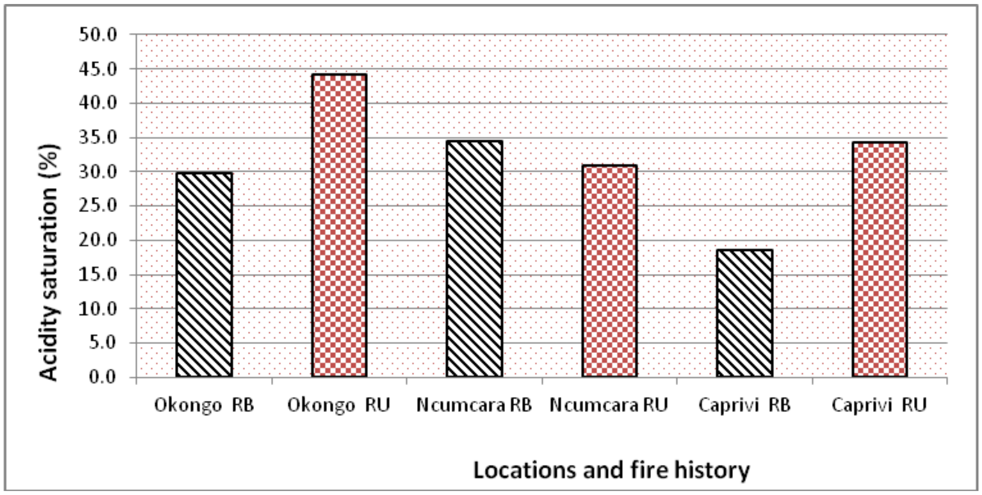


Figure 0.26: Acid saturation in recently burnt and unburnt treatments across the three locations (RB = Recently burnt, RU = Recently unburnt).

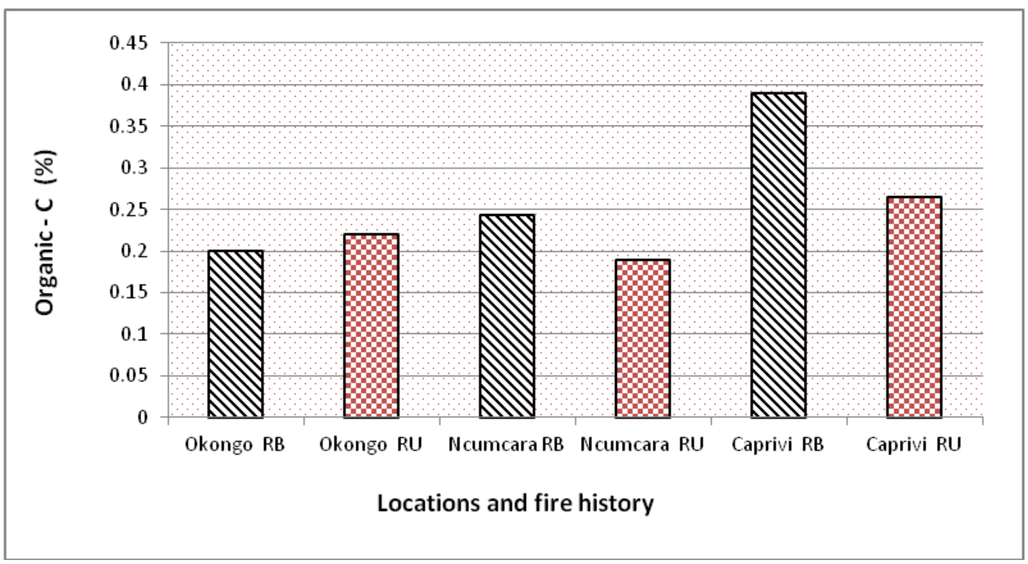


Figure 0.27: Organic carbon (C) contents across location and treatment combinations (RB = Recently burnt, RU = Recently unburnt).

4.4 *Pterocarpus angolensis* size structure

The frequency distributions of DBH and height classes are shown in Figures 4.16 and 4.17. A large proportion of trees in all study locations are in the DBH class of 0 – 10 cm. Mainly in Caprivi, recently burnt treatments recorded a higher number of trees in all the DBH classes than recently unburnt treatments (Figure 4.16). Figure 4.17 illustrates few trees in the height class of 0 – 0.5 m in all locations. The highest number of trees is noted in the height class of 0.6 – 1.0 m in Okongo but in Ncumcara and Caprivi is recorded in the height class of 1.1 – 1.5 m. Again, recently burnt had higher number of trees in all the height classes except in Okongo.

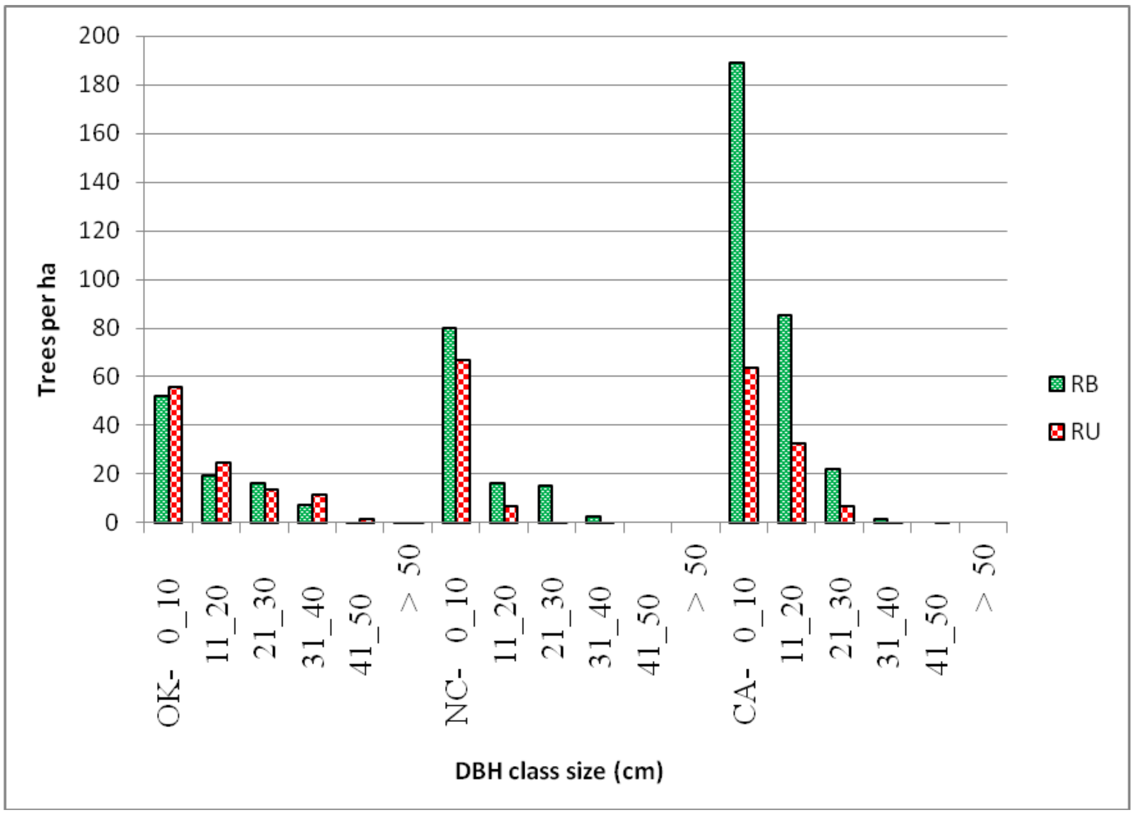


Figure 0.28: Frequency distributions across tree DBH classes (Ok – Okongo, NC – Ncumcara, CA – Caprivi). These are trees with height of 1.3 m and more.

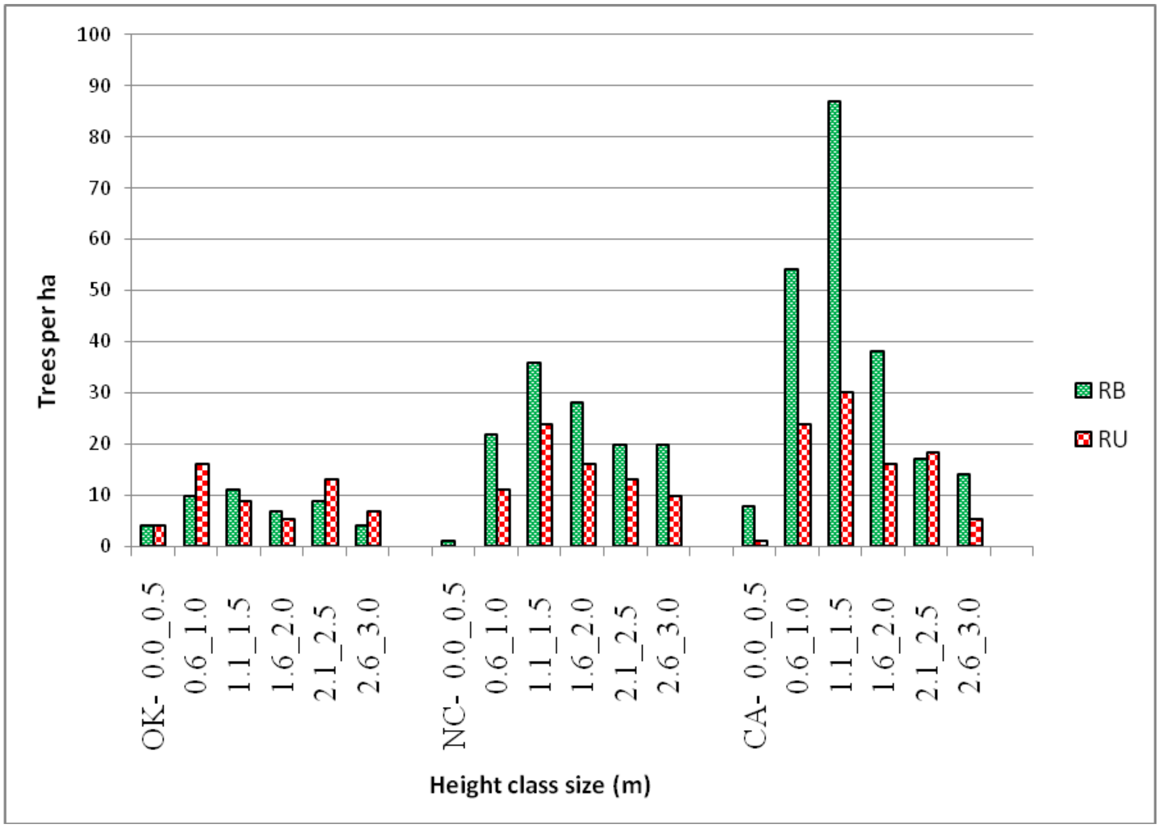


Figure 0.29: Frequency distributions across tree height classes (Ok – Okongo, NC – Ncumcara, CA – Caprivi**)**. These are seedlings and saplings of 3 m high and lower

4.5 Stocking analysis, tree stage basal area and DBH

The investigation was carried out to determine the overall *Pterocarpus angolensis* tree stocking, tree basal area and DBH as well as abundances of seedlings, saplings and mature trees in the three study locations. The statistical analysis is performed at confidence interval of 0.95 (95%) and significance level of 0.05 (5%) to determine statistical significance of tree size structure between locations and between fire history treatments. All the descriptive statistics in this section follow the following pattern: The frequency diagram across size classes shows frequency on horizontal axis and classes on vertical axis. The box and whisker plot shows the median (small square marker), lower and upper quartiles (box), standard deviations (whiskers) as well as outliers above and below the whiskers. Summary statistics for the variables stocking, basal area, DBH as well as abundances of seedlings, saplings and mature trees are shown in Figure 4.18. In addition, Figures 4.19 – 4.20 show significance differences of saplings and mature trees abundances between study locations and between fire history treatments.

The data of the stocking and basal area were not normally distributed and were therefore transformed into a logarithmic scale. The stocking for all the three study locations ranges from 19 to 523 trees per ha as there are other tree species and plants found in the forests. Mature tree abundance has the highest mean followed by saplings then seedlings (Figure 4.18). The interaction between location and fire history on seedling abundance was analysed and found to be not significant (details not presented). Similarly, seedling abundance between locations and between fire histories was not significantly different. It can therefore be concluded that seedling abundance was effectively similar across burning history treatments and locations.

Sapling abundance data do not show an interaction between locations and fire histories as well as no significant difference between fire history treatments. The highly significant difference (p <0.001) is between locations whereby Ncumcara has the highest sapling abundance (Figure 4.19). Table 4.8 presents significant difference between all study locations.

There is no significant interaction in combination of locations and fire history and also the difference between fire histories is non-significant on mature tree abundance. However, highly significant differences exist between locations whereby Ncumcara and Caprivi have lower abundance of mature trees **(**Figure 4.20**)**. The significant differences are among all study locations **(**Table 4.9**).**

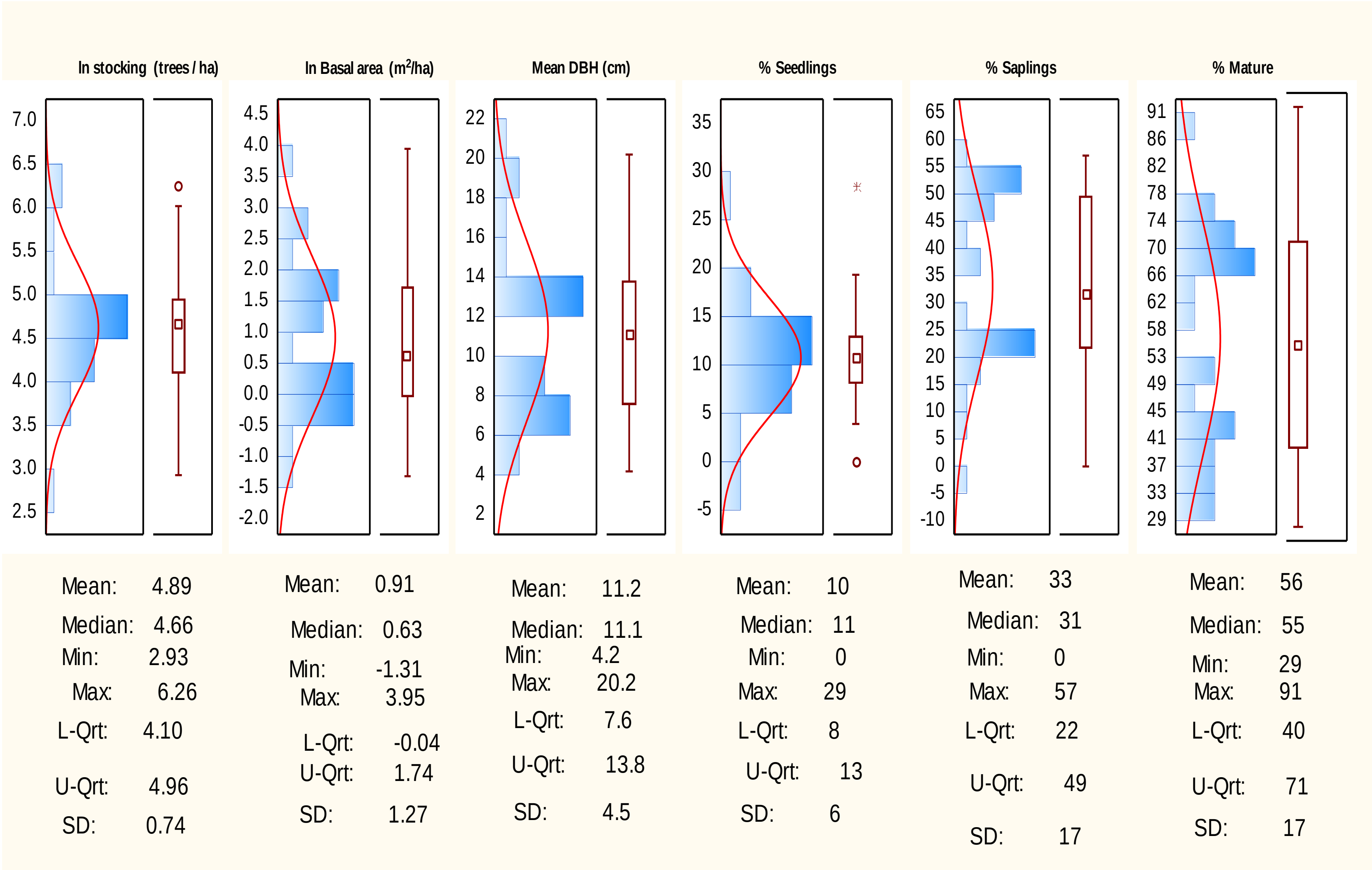


Figure 0.30: Descriptive statistics for *ln* stocking/ha, *ln* Basal area, mean DBH and abundance of seedlings, saplings and mature trees derived from population data sets.

Table 0.9: Multiple comparison tests (Fisher's LSD) on saplings percentages

Study location	Okongo	Ncumcara
Ncumcara	<0.001	
Caprivi	0.004	0.024

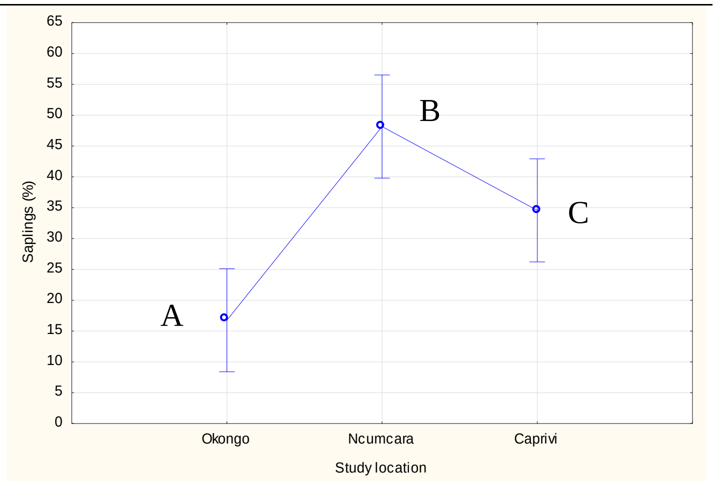


Figure 0.31: Differences of saplings abundance between study locations. Locations with the same letter are not significantly different.

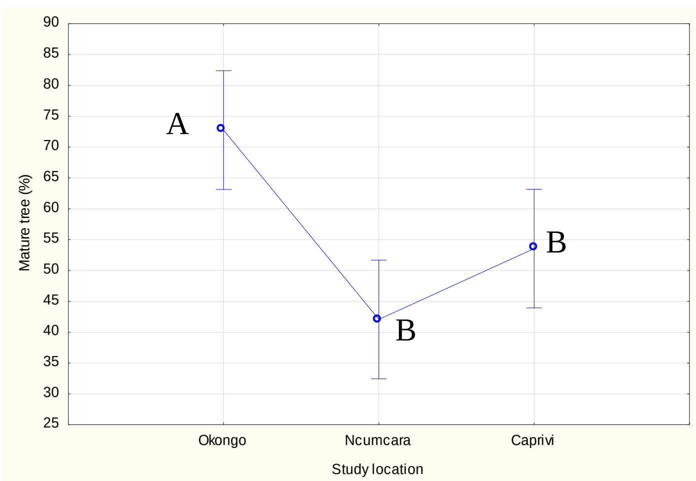


Figure 0.32: Differences in the abundance of mature trees between study locations. Locations with the same letter are not significantly different.

Table 0.10: Multiple comparison tests (Fisher's LSD) on mature tree abundance

Study location	Okongo	Ncumcara
Ncumcara	<0.001	
Caprivi	0.007	0.089

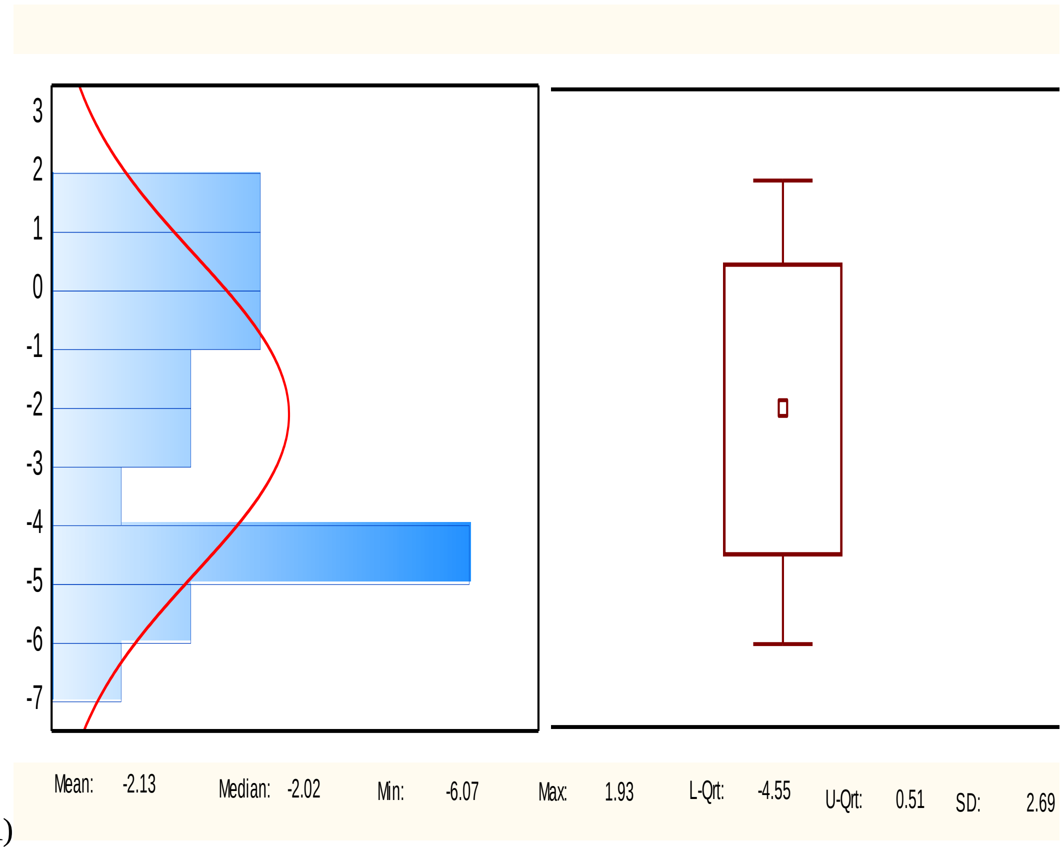
4.6 Tree stage Basal Area and DBH

4.6.1 Sapling analysis

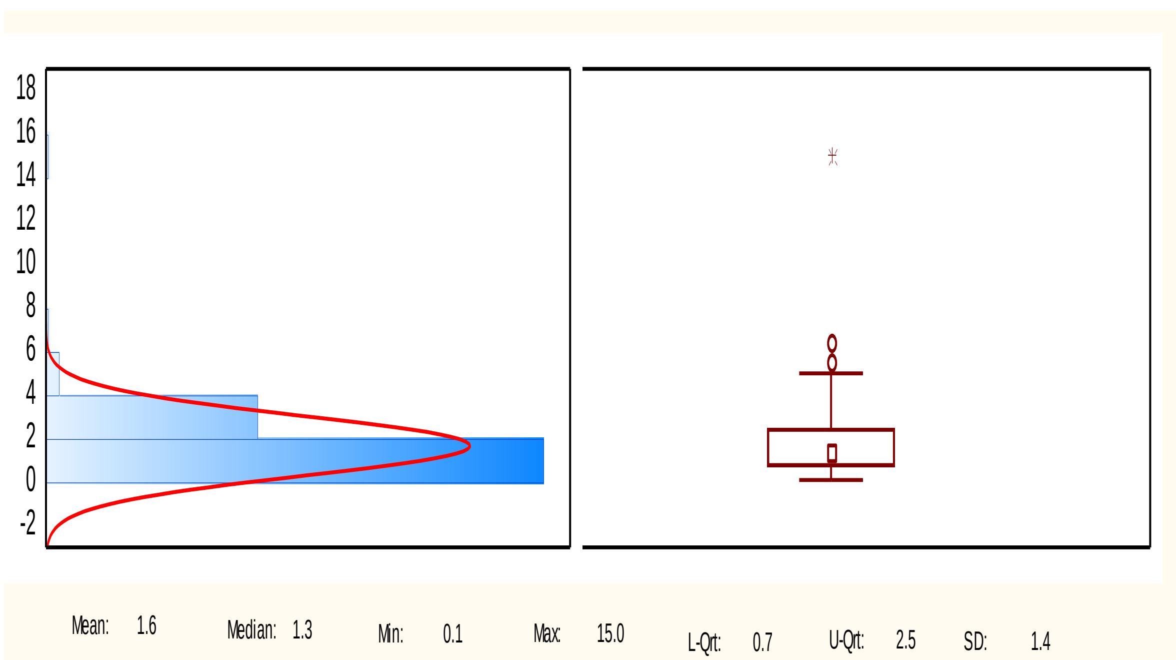
4.6.1.1 Basal Area and DBH analysis

The basal area and DBH of saplings of all the three study locations were calculated to assess their differences and if they are influenced by different fire history treatments. The basal area data was found non-normal and transformed into logarithmic scale. Figure 4.21 (A) and (B) indicates the maximum BA as 6.68 m^2 ha^{-1} and DBH as 15.0 cm. There is no significant interaction between locations and fire history.

When main effects were examined highly significant difference existed between fire histories but not significant between locations. The BA is highest in recently unburnt treatment (Figure 4.22). The DBH was found not significantly different between fire history and the interaction between locations and fire history was also non-significant. The only significant difference was discovered between locations (p = 0.007) (Figure 4.23). The significant difference was between Okongo and Caprivi as well as between Ncumcara and Caprivi **(**Table 4.10**).**



A)



B)

Figure 0.33: Descriptive statistics for *ln* Basal Area (A) and DBH (B) for saplings from the population data set.

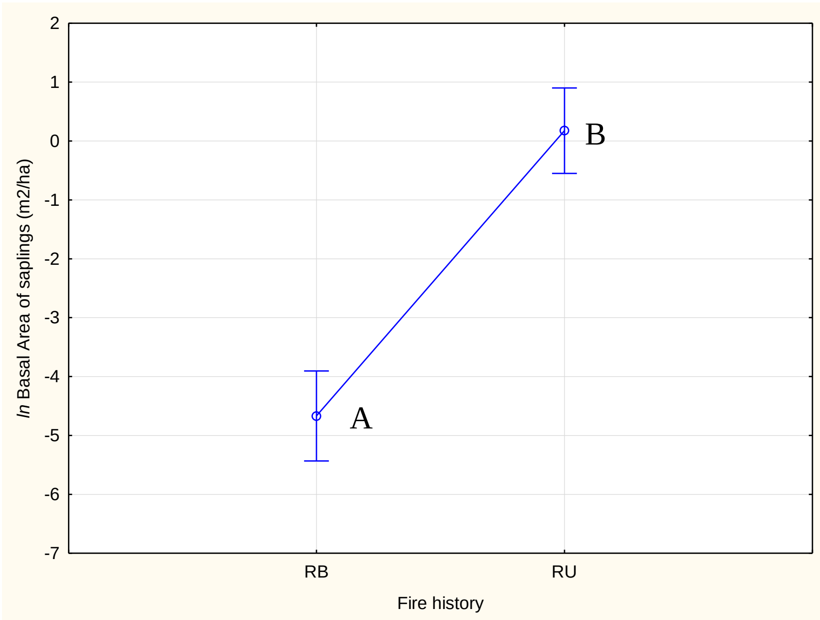


Figure 0.34: Differences of *ln* Basal Area for sapling size classes between fire history treatments. Fire history treatments with the same letter are not significantly different.

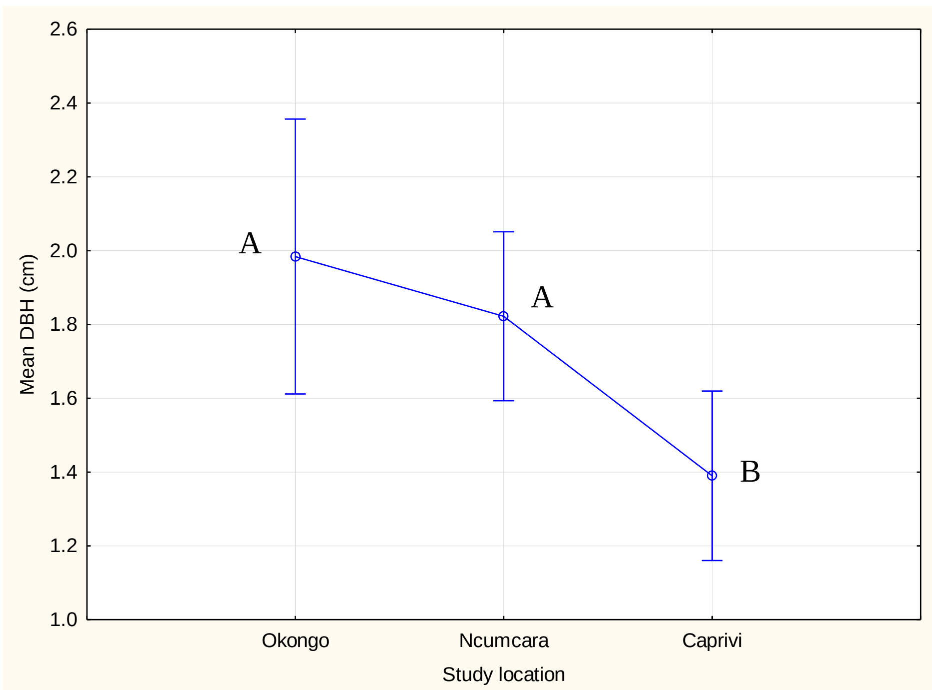


Figure 0.35: Differences of mean DBH of saplings between study locations. Locations with the same letter are not significantly different.

Table 0.11: Multiple comparison tests (Fisher's LSD) on mean DBH

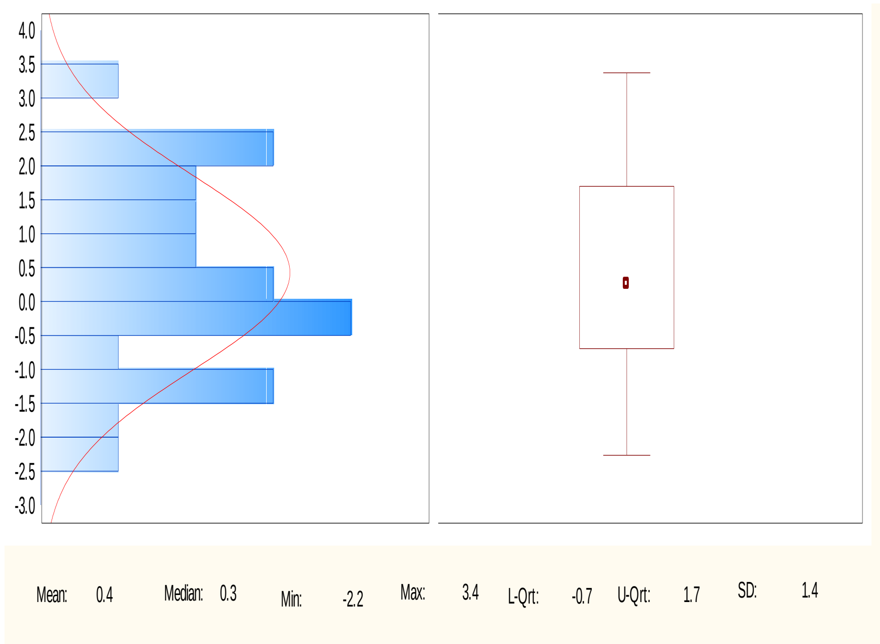
Location	Okongo	Ncumcara
Ncumcara	0.606	
Caprivi	0.011	0.005

4.6.2 Bole tree analysis

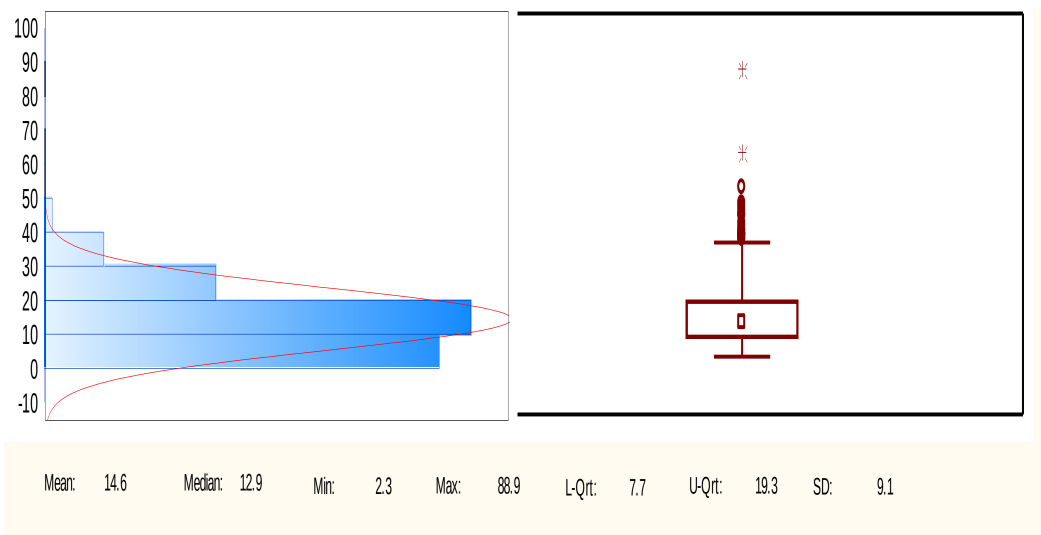
4.6.2.1 Basal Area and DBH analysis

The basal area and DBH of the bole tree were also analysed to investigate if there is a difference with that of the saplings. As for saplings, the basal area data was transformed into logarithmic scale. The mean of the BA is 1.52 m^2 ha^{-1} with a maximum of 29.37 m^2 ha^{-1} (Figure 4.24 (A)). It was found that BA had no significant interaction between locations and fire histories. Again the difference of BA between locations and between fire histories was not significant.

The mean for the DBH was 14.6 cm which is much less than the maximum DBH of 88.0 cm (Figure 4.24 (B)). There was a highly significant interaction observed between locations and fire history on mean DBH and therefore the main effects were not analysed. The significant interaction was due to the noticeable trend between Ncumcara recently burnt (RB) and recently unburnt (RU) combinations (Figure 4.25**)**. Table 4.11 indicates location and burning history combinations significances in red numbers.



(A)



(B)

Figure 0.36: Descriptive statistics for *ln* Basal Area (A) and DBH (B) for trees in the bole size class from the population data set.

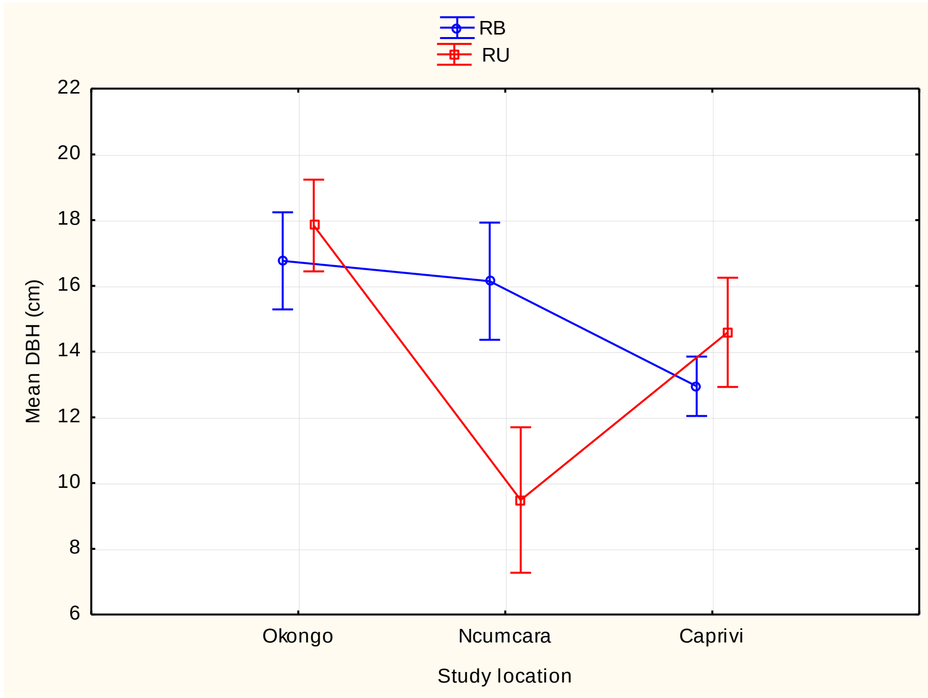


Figure 0.37: The interaction of locations and fire history on mean DBH of bole trees.

Table 0.12: Multiple comparison tests (Fisher's LSD) on mean DBH of bole trees

Study location & fire history	Okongo RB	Okongo RU	Ncumcara RB	Ncumcara RU	Caprivi RB
Okongo RU	0.299				
Ncumcara RB	0.601	0.143			
Ncumcara RU	<0.001	<0.001	<0.001		
Caprivi RB	<0.001	<0.001	0.002	0.005	
Caprivi RU	0.055	0.003	0.210	<0.001	0.089

4.7 Tree developmental stages: destructive analysis

4.7.1 Seedling analysis

4.7.1.1 Taproot measurements

This section focuses on the analysis if taproot parameters differs from study location to study location and also if different fire history treatments influences taproot parameters differently. Figure 4.26 illustrates taproot mass and length with large outliers that might influence the distribution of the data. Taproot mass formed a positively skewed distribution while taproot depth formed a negatively skewed distribution.

The significant interaction existed in the combination of locations and burning history on taproot mass (p = 0.004) (Figure 4.27). As a result the main effects were not analysed. The combinations of locations and burning history that were significantly different are shown in Table 4.12. The difference of taproot diameter and depth were not significant between locations and between burning histories. Again the interaction is not significant on taproot diameter and length. Mean values for taproot and shoot variables derived and de-transformed from Figures 4.26, 4.28, 4.42 & 4.43 are presented in Table 4.24.

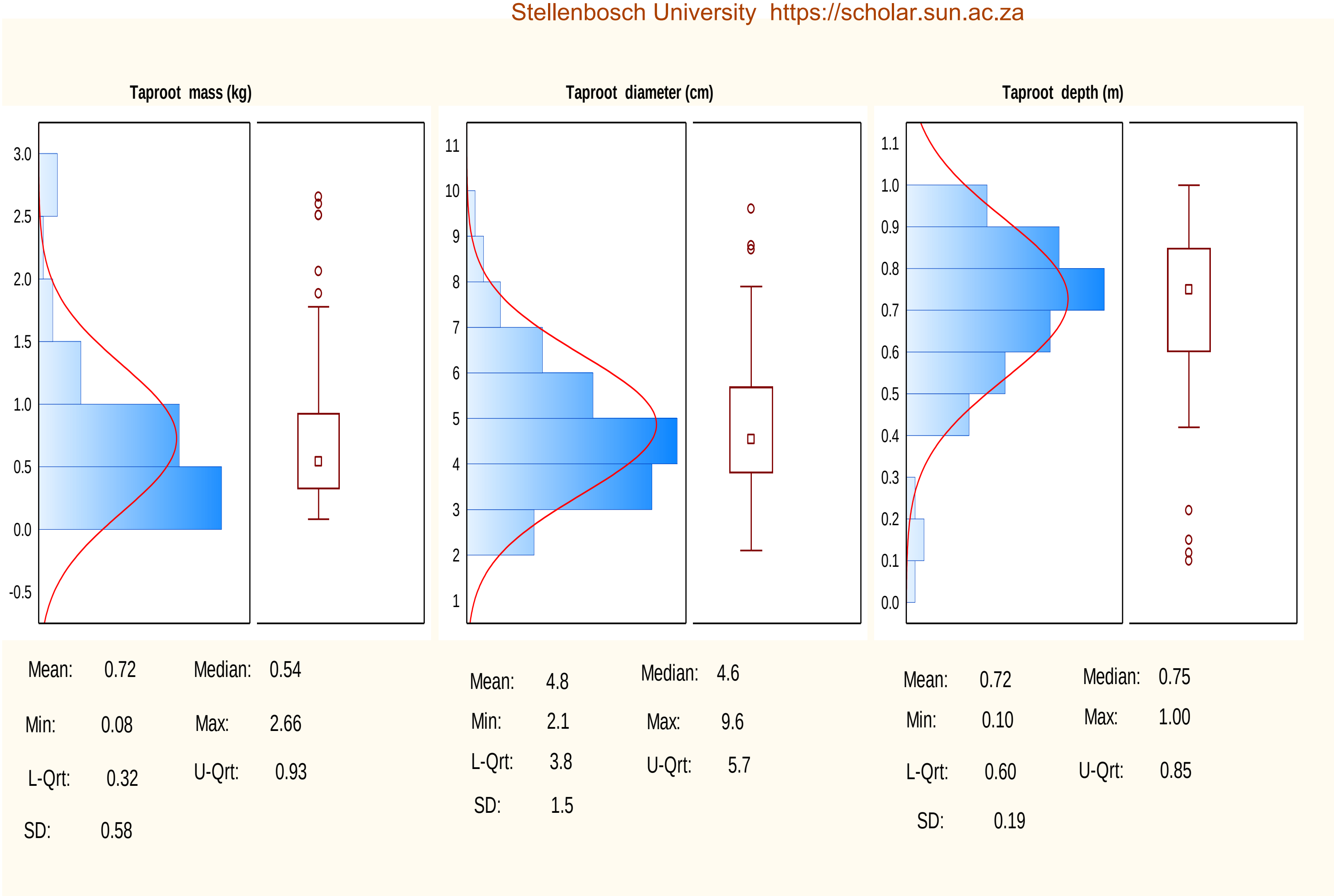


Figure 0.38: Descriptive statistics for mean taproot mass, diameter and length per plot measurements from the destructive sample data set.

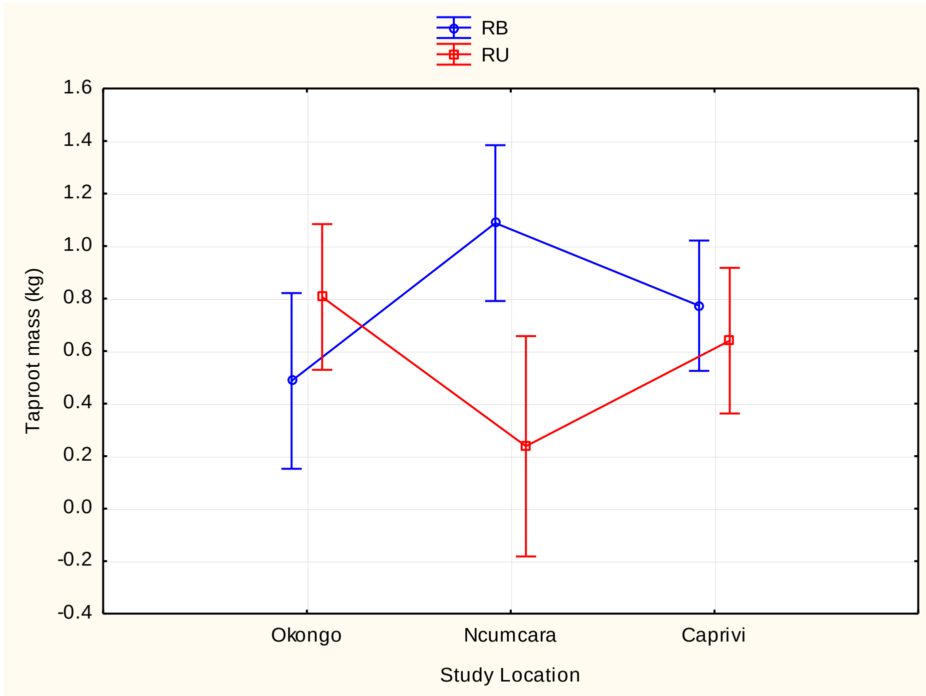


Figure 0.39: Differences of taproot mass of seedlings between study locations.

Table 0.13: Multiple comparison tests (Fisher's LSD) on taproot mass

Study Location & fire history	Okongo RB	Okongo RU	Ncumcara RB	Ncumcara RU	Caprivi RB
Okongo RU	0.147				
Ncumcara RB	0.009	0.172			
Ncumcara RU	0.359	0.027	0.001		
Caprivi RB	0.175	0.859	0.109	0.032	
Caprivi RU	0.484	0.401	0.031	0.115	0.479

4.7.1.2 Shoot variables

Shoot variables such as shoot mass and height were statistically analysed to determine their differences between locations and between fire histories. Both shoot mass and height dataset were transformed into logarithmic scale to satisfy the normality assumption. The observed outliers formed a long negative tail. Figure 4.28 presents location measurements of shoot mass and height. The significance difference of shoot mass was only observed between locations. This significant difference is obvious as Okongo indicated the lowest while Ncumcara indicated the highest (Figure 4.29 & Table 4.13). The difference on shoot height was found not significant between locations and between burning history and again no significant interactions existed. The combination of locations and fire history treatments shows weak significant interaction on shoot mass as a percentage of taproots mass. This significant interaction might be due to higher shoot mass percentage on the combination of Ncumcara and RU treatments (Figure 4.30 & Table 4.45).

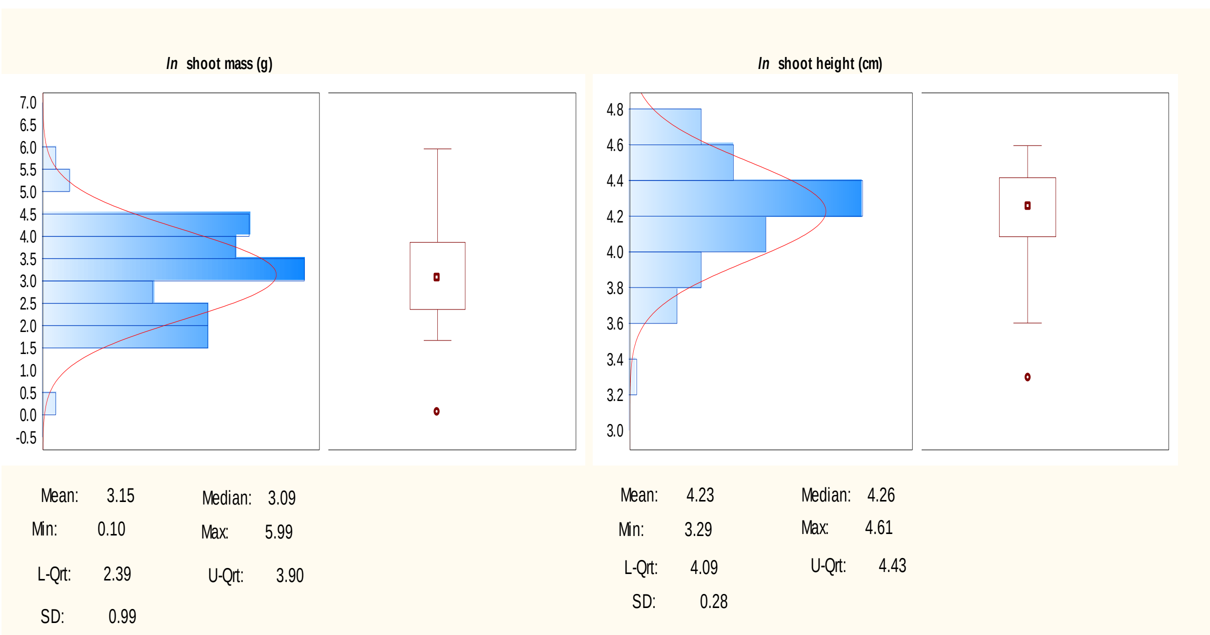


Figure 0.40: Descriptive statistics of shoot variables of the seedlings

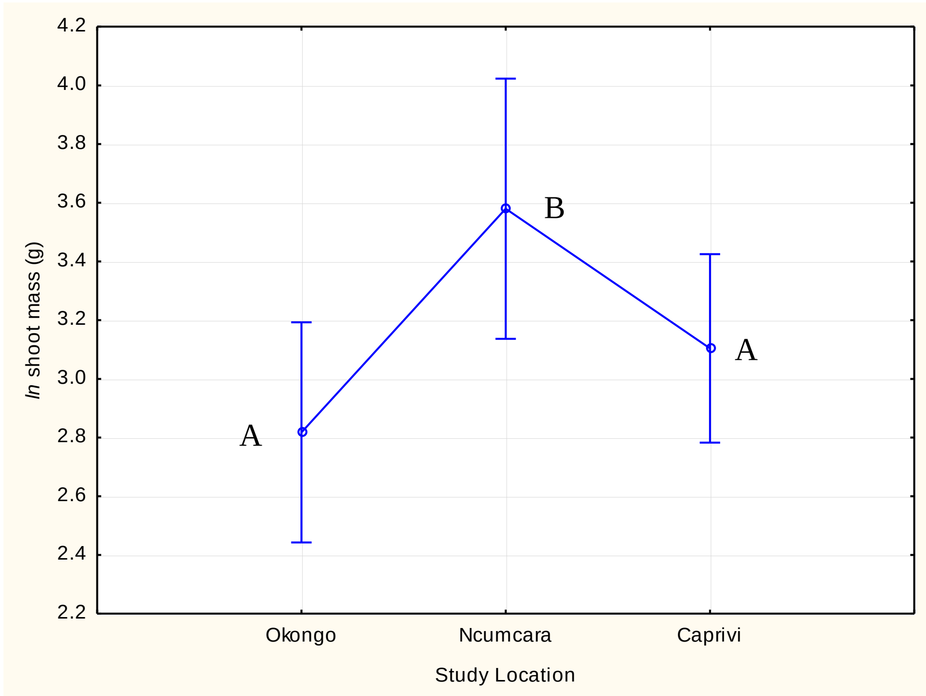


Figure 0.41: Differences of *ln* shoot mass of seedlings between locations. Locations with the same letter are not significantly different.

Table 0.14: Multiple comparison tests (Fisher's LSD) on *ln* shoot mass

Study Location	Okongo	Ncumcara
Ncumcara	0.005	
Caprivi	0.303	0.038

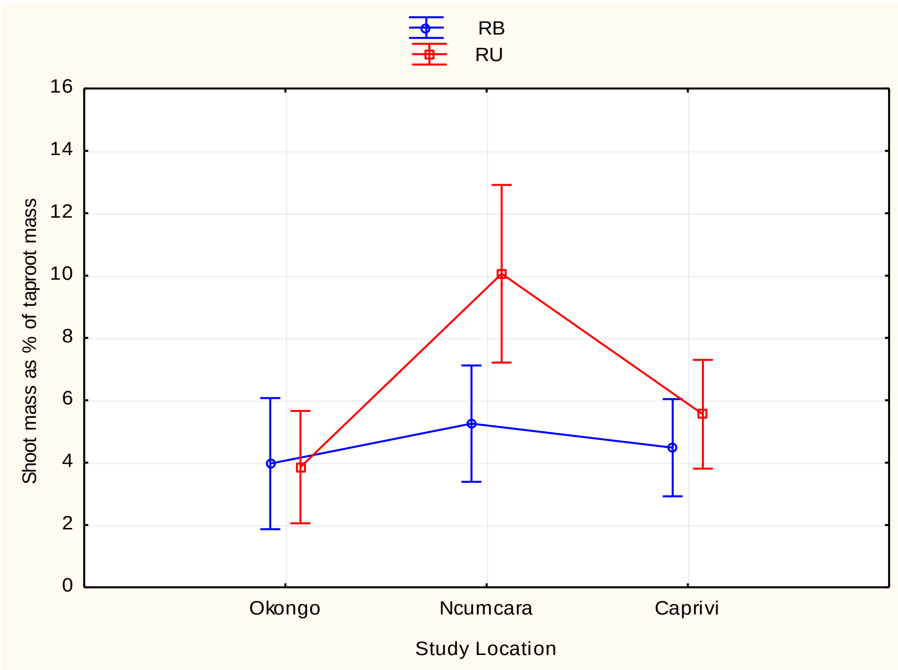


Figure 0.42: The interaction of study locations and fire histories on shoot mass as percentage of taproot mass for seedlings.

Table 0.15: Multiple comparison tests (Fisher's LSD) on shoot mass as percentage of taproot mass for seedlings

Study Location & fire history	Okongo RB	Okongo RU	Ncumcara RB	Ncumcara RU	Caprivi RB
Okongo RB	0.936				
Ncumcara RB	0.365	0.287			
Ncumcara RU	<0.001	<0.001	0.006		
Caprivi RB	0.698	0.604	0.528	0.001	
Caprivi RU	0.252	0.182	0.815	0.008	0.364

4.7.1.5 Non-structural carbohydrate (NSC) storage

Trees, especially suffrutices require non-structural carbohydrates for survival during phases of above-ground die-back. Hence, this section highlights statistically significant results of the sugars and starch contents between study locations and between fire history treatments. NSC storage was tested for the normality assumption and we found non-normal. The data was transformed into logarithmic scale.

The mean of oligosaccharides and polysaccharides are almost similar but the mean of starch is a bit higher (Figure 4.31). The significant interaction existed between locations and fire history treatments ($p = 0.007$) on oligosaccharides. Even though the main effects could not be analysed, the significant difference between burning histories showed oligosaccharides highest in recently burnt treatments (graph not shown). The interaction between locations and burning history is significant on both polysaccharides and starch ($p < 0.001$) (Figures 4.32 & 4.34). Tables 4.15 & 4.17 indicate significant interactions between locations and burning history. The significant interaction for non-structural carbohydrates storage is due to the trend of the combination of Ncumcara recently burnt (RB) and recently unburnt (RU) treatments.

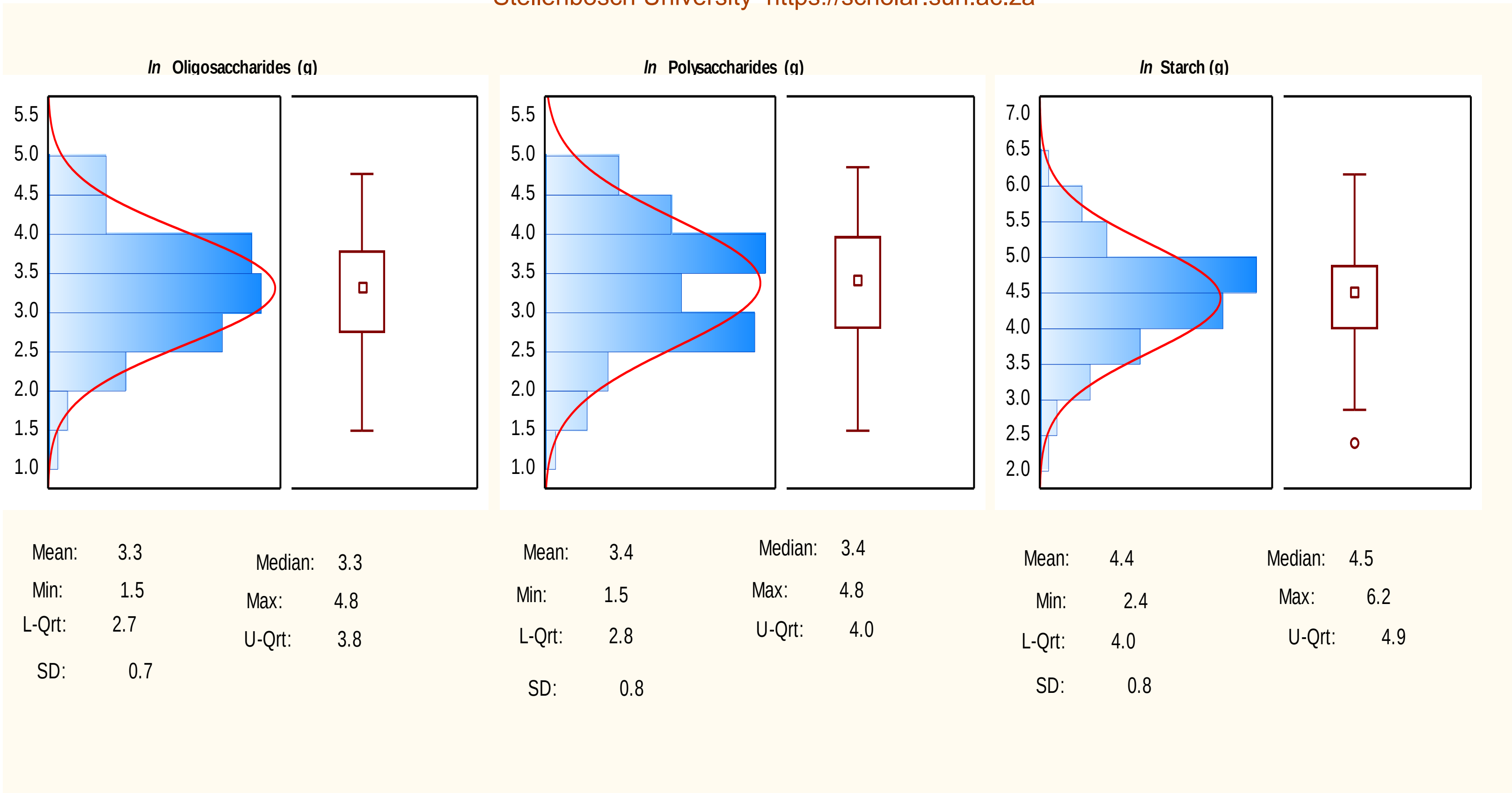


Figure 0.43: Descriptive statistics of non-structural carbohydrates storage of the seedlings.

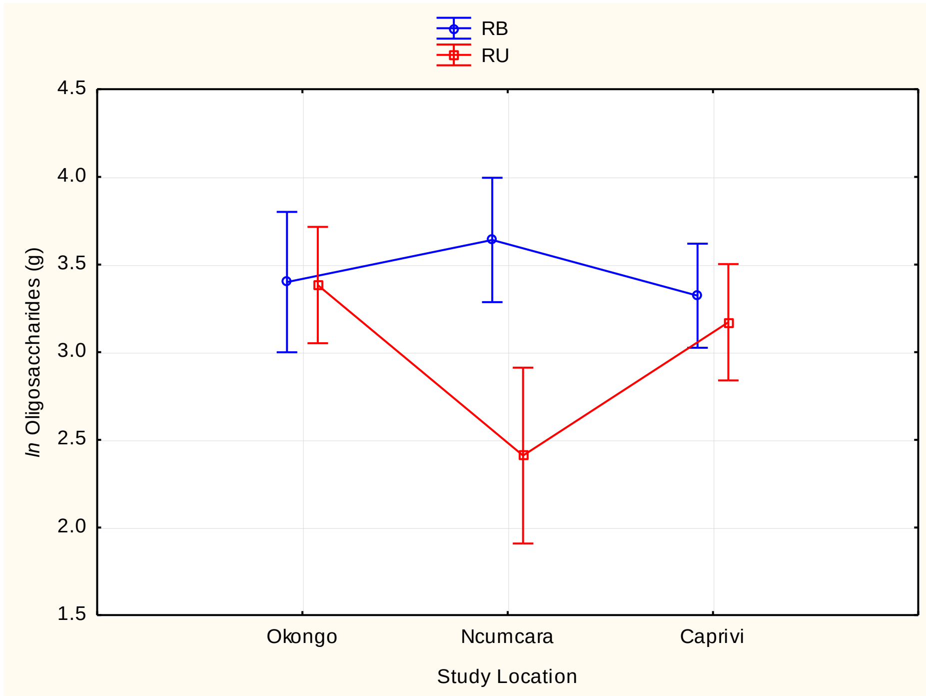


Figure 0.44: The interaction of study locations and fire histories on *ln* oligosaccharide storage in the taproots of seedlings.

Table 0.16: Multiple comparison tests (Fisher's LSD) on mean *ln* oligosaccharides

Study Location & fire history	Okongo RB	Okongo RU	Ncumcara RB	Ncumcara RU	Caprivi RB
Okongo RB	0.947				
Ncumcara RB	0.374	0.295			
Ncumcara RU	0.003	0.002	<0.001		
Caprivi RB	0.757	0.787	0.175	0.003	
Caprivi RU	0.382	0.371	0.058	0.014	0.500

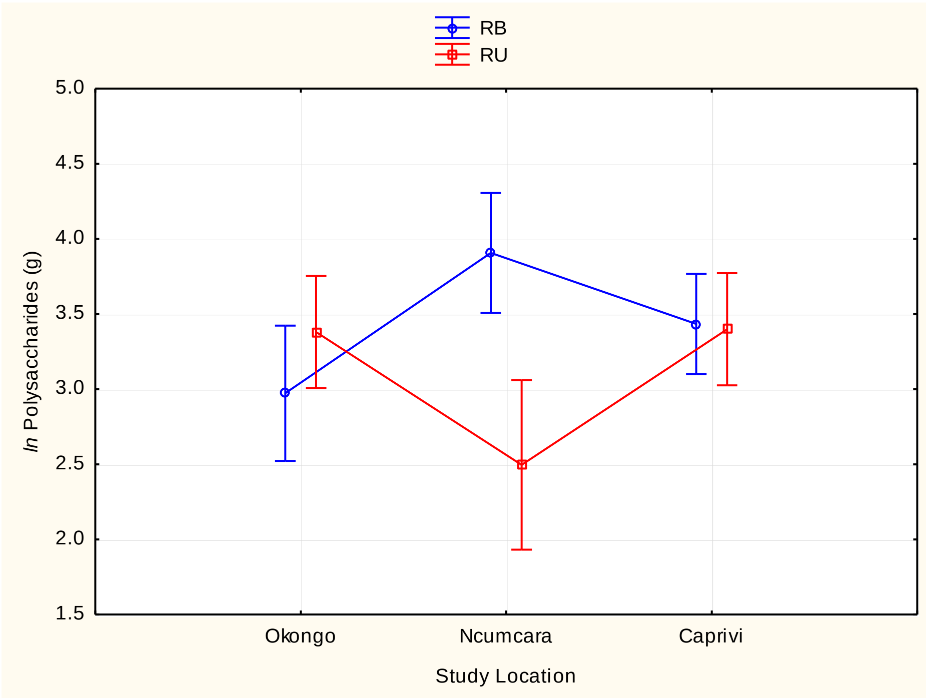


Figure 0.45: The interaction of study locations and fire histories on *ln* polysaccharides of seedlings.

Table 0.17: Multiple comparison tests (Fisher's LSD) on *ln* Polysaccharides of seedlings

Study Location & fire history	Okongo RB	Okongo RU	Ncumcara RB	Ncumcara RU	Caprivi RB
Okongo RB	0.170				
Ncumcara RB	0.003	0.059			
Ncumcara RU	0.192	0.011	0.001		
Caprivi RB	0.106	0.832	0.074	0.006	
Caprivi RU	0.151	0.945	0.068	0.010	0.890

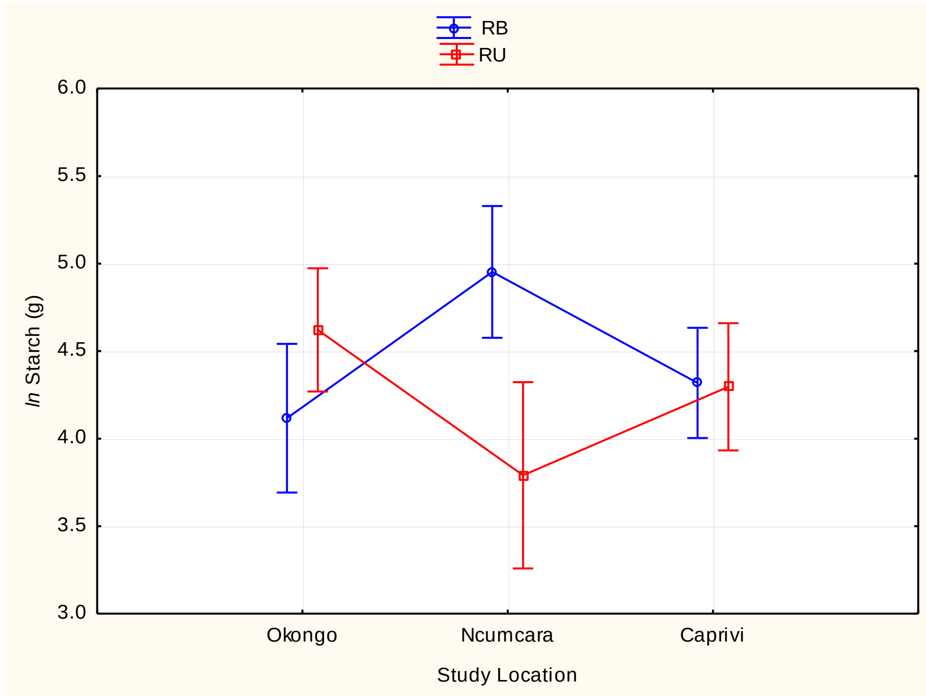


Figure 0.46: The interaction of study locations and fire histories on *ln* starch of seedlings.

Table 0.18: Multiple comparison tests (Fisher's LSD) on *ln* Starch of seedlings

Study Location & fire history	Okongo RB	Okongo RU	Ncumcara RB	Ncumcara RU	Caprivi RB
Okongo RB	0.072				
Ncumcara RB	0.004	0.204			
Ncumcara RU	0.343	0.011	<0.001		
Caprivi RB	0.451	0.205	0.012	0.094	
Caprivi RU	0.525	0.205	0.015	0.123	0.927

4.7.1.3 Relationship between taproot variables

The statistical significant relationship between taproots mass, taproot diameter and length were analysed and presented in this section. Figure 4.35 indicates strong linear relationship between taproot diameter and taproot mass ($p < 0.001$) with correlation coefficient (R) = 0.78 while the coefficient of determination (R^2) = 0.60. The correlation coefficient of 0.78 indicates a strong positive correlation of the relationship between taproot diameter and mass. So, as the taproot diameter increases the taproot mass also increases, which is to be expected.

From the coefficient of the simple regression, if the taproot diameter is increased by one unit, the taproot mass is estimated on average to increase by 0.30 kg (Table 4.18). The coefficient of determination of 0.60 means 60% of the variation in taproot diameter can be explained by the variation in taproot mass.

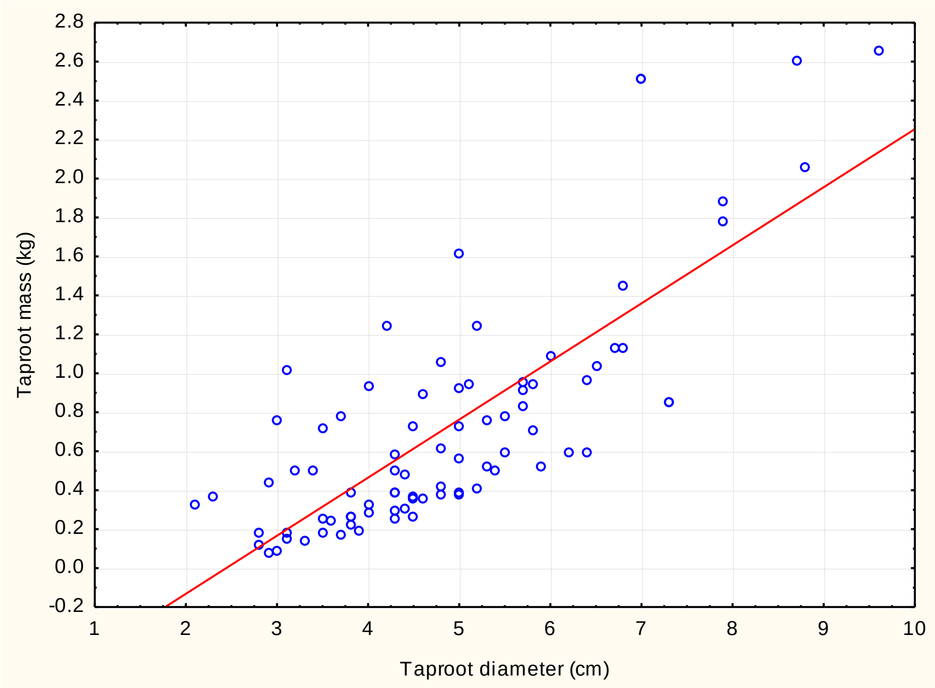


Figure 0.47: The relationship between taproot mass and taproot diameter of seedlings.

Table 0.19: Linear regression output to determine the effect of taproot diameter on taproot mass; R = 0.78, R^2 = 0.61, Adjusted R^2 = 0.60

	b*	Std.Err. of b*	b	Std.Err.of b	t(82)	p-value
Intercept			-0.728	0.135	-5.376	<0.001
Tuber diameter (cm)	0.779	0.069	0.298	0.027	11.235	<0.001

4.7.1.4 Relationship taproot mass and shoot variables

This section highlights results on the analysis of relationship between taproot mass and shoot mass and height. A very weak relationship existed between *ln* shoot mass and taproot mass with correlation coefficient (R) = 0.44 while coefficient of determination (R^2) = 0.20.

Correlation coefficient of 0.44 presents a positive correlation of the relationship between shoot mass and taproot mass (Table 4.19).

The coefficient of determination of 0.20 means only 20 % of the variations in shoot mass can be explained by the variation in taproot mass. So, taproot mass has a weak positive effect on shoot mass meaning other factors might exert a much greater effect on shoot mass. This implies that the taproot mass is not a good predictor of the shoot mass. There was no relationship between taproot mass and shoot height. The coefficient of determination of 0.15 means only 15 % of the variation in shoot height can be explained by the variation in taproot mass (Table 4.20).

Table 0.20: Linear regression output to determine the effect of taproot mass on shoot mass; $R=0.44$, $R^2=0.20$, Adjusted $R^2= 0.20$.

	b*	Std.Err.of b*	b	Std.Err.of b	t(82)	p-value
Intercept			2.613	0.155	16.821	<0.001
Taproot mass (kg)	0.445	0.100	0.752	0.167	4.505	<0.001

Table 0.21: Linear regression output to determine the effect of taproot mass on *ln* shoot height. R= 0.39, R^2= 0.16, Adjusted R^2= 0.15

	b*	Std.Err.of b*	b	Std.Err.of b	t(82)	p-value
Intercept			4.096	0.044	92.383	<0.001
Taproot mass (kg)	0.395	0.101	0.185	0.048	3.892	<0.001

4.7.1.6 Relationship of non-structural carbohydrate (NSC) storage with taproot variables

Non-structural carbohydrates storage consist of different types of sugars (oligosaccharides, polysaccharides) and starch that were statistically analysed to determine their contents per taproot and their mean content per location and burning history. All sugars (oligosaccharides, polysaccharides) and starch had significant effects and strong correlation relationship with taproot mass (Figures 4.36 & 4.38). The correlation coefficients of 0.84 – 0.86 indicated a strong positive correlation of the relationship between taproot mass and sugars and starch. The reason for the strong correlation is the fact the sugar and starch content is obtained by multiplying their concentrations with the taproot mass, and furthermore that the concentration of sugars and starch varied in a comparatively narrow band while the masses differed more widely between individual samples. For every unit increase in the taproot mass, the oligosaccharide content is estimated to increase on average by 2.8 g. If taproot mass increases by one unit polysaccharides increases on average by 3.2 g while for every unit increase on taproot mass starch increases by 3.0 g (Tables 4.21 – 4.23**).**

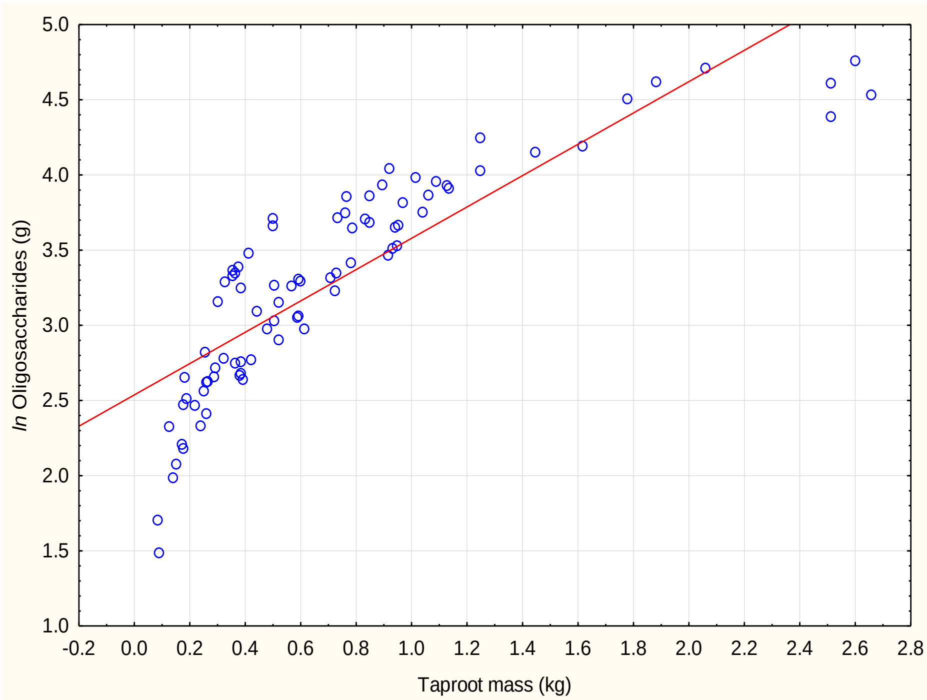


Figure 0.486: The relationship between taproot mass and *ln* oligosaccharides content of seedlings

Table 0.22: Linear regression output to determine the effect of taproot mass on *ln* oligosaccharides; R= 0.86, R^2= 0.73, Adjusted R^2= 0.73

	b*	Std.Err. of b*	b	Std.Err. of b	t(82)	p-value
Intercept			2.538	0.064	39.449	<0.001
Taproot mass (kg)	0.857	0.057	1.041	0.069	15.069	<0.001

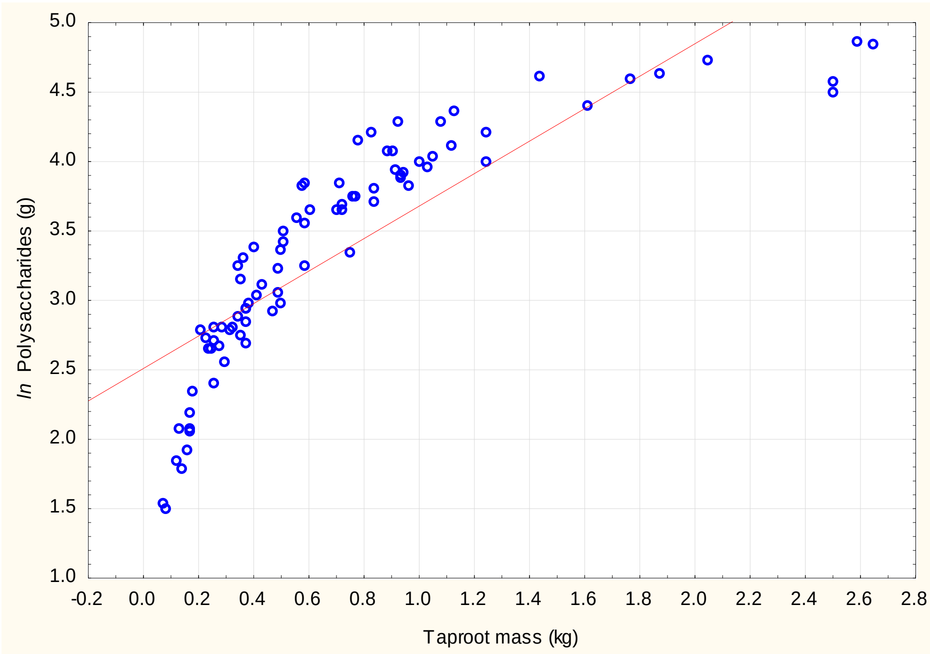


Figure 0.49: The relationship between taproot mass and *ln* Polysaccharides of seedlings

Table 0.23: Linear regression output to determine the effect of taproot mass on *ln* Polysaccharides. R= 0.84, R^2= 0.71, Adjusted R^2= 0.71

	b*	Std.Err.of b*	b	Std.Err. of b	t(82)	p-value
Intercept			2.510	0.076	32.859	<0.001
Taproot mass (kg)	0.844	0.059	1.170	0.082	14.244	<0.001

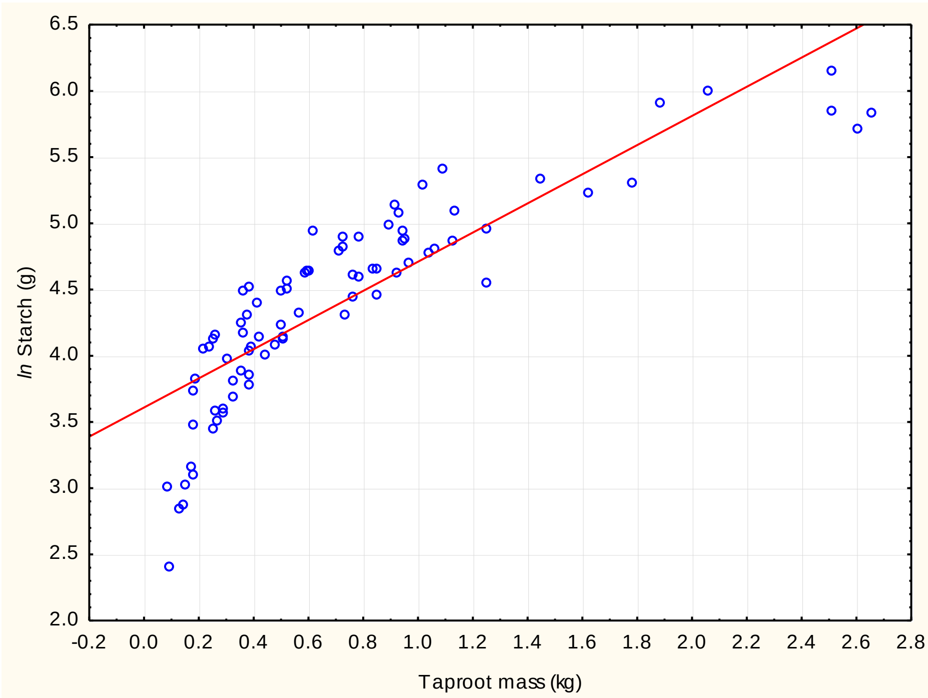


Figure 0.508: The relationship between taproot mass and *ln* starch of seedlings

Table 0.24: Linear regression output to determine the effect of taproot mass on *ln* starch; R= 0.86, R^2= 0.73, Adjusted R^2= 0.73

	b*	Std.Err.of b*	b	Std.Err.of b	t(81)	p-value
Intercept			3.609	0.069	52.367	<0.001
Taproot mass (kg)	0.856	0.057	1.101	0.074	14.913	<0.001

4.7.1.7 Tree growth ring counts

Cross - dating was performed to determine the ages of the seedlings by counting the number of growth rings on the taproot neck (part between taproot and shoot). The mean tree growth rings was 9 and most of the growth rings range between 5 and 13. However, maximum growth ring number recorded was 21, which appears to be an outlier (Figure 4.39). The growth rings count was recorded as an average of two radii per sample. There is no observed significant interaction between locations and burning history for growth ring count. Furthermore, there is no significant difference on growth rings between locations as well as between burning history treatments.

The non-structural carbohydrate contents of taproots were plotted as a function of growth ring number to determine if tree age had an effect on the accumulation of non-structural carbohydrate storage (Figure 4.40). Based on Figure 4.40 fitting lines (R^2 = 0.43 & 0.42 respectively) for polysaccharides and starch were weak, because there is a lot of variability between trees with growth ring counts of 5 to 10. The starch showed a strong increase as growth ring number increased while oligosaccharides showed a fairly good regression line fit (R^2 = 0.66). It appears that large quantities of sugars and starch are accumulated with age (Figure 4.40).

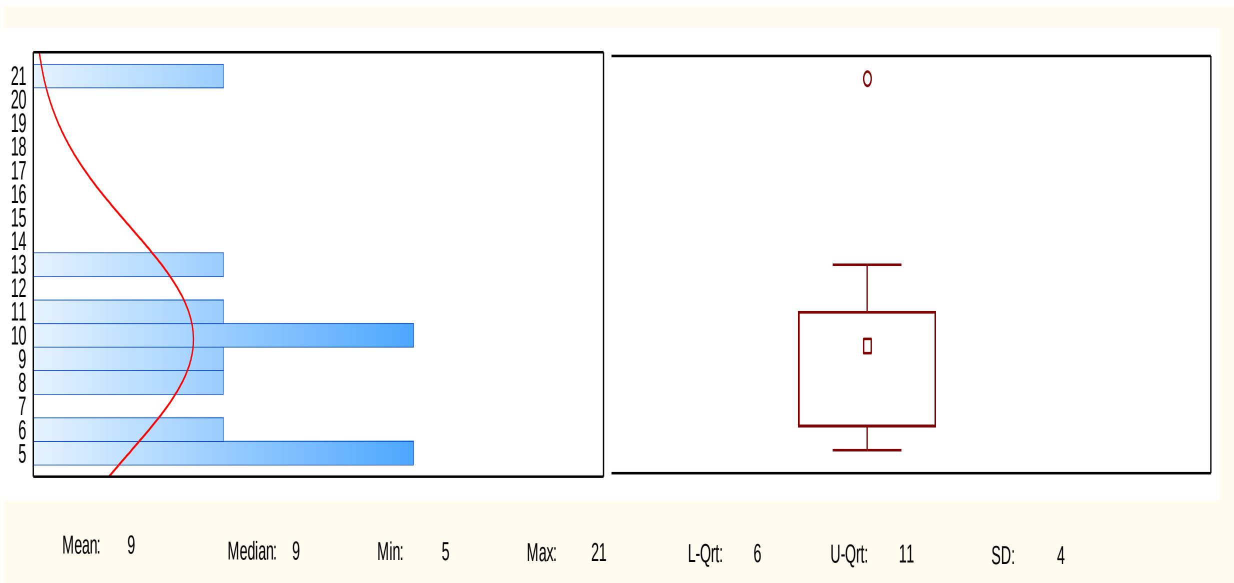


Figure 0.5139: Descriptive statistics of tree growth ring counts of the seedlings

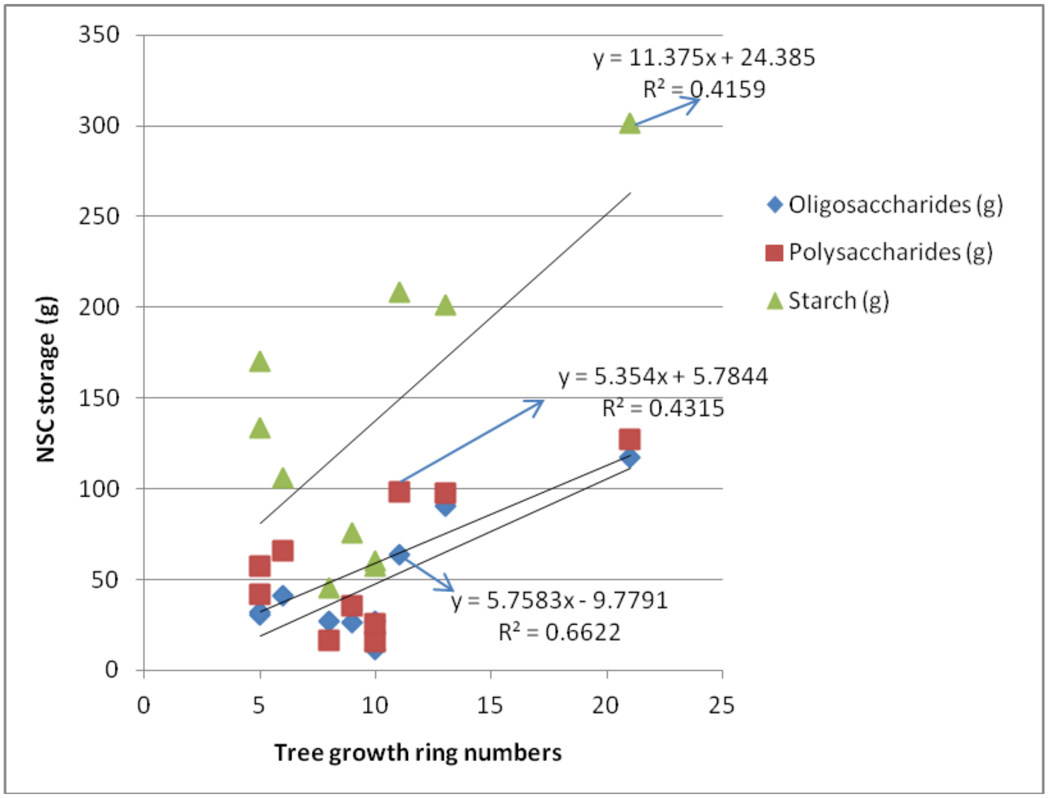


Figure 0.52: The relationship between tree growth rings and non-structural carbohydrates storage of seedling taproots

4.7.2 Sapling analysis

4.7.2.1 Taproot measurements

Taproot parameters of saplings were analysed and this section presents statistical results on significant differences between study locations and between fire history treatments. Taproot mass and diameter had outliers that formed a positively skewed distribution while taproot depth outliers caused a long negative tail. Taproot mass formed a positive tail while taproot depth formed negative tail. Most of the taproots had mass between 0.5 to 1.5 kg, taproot diameter was mainly between 4 and 6 cm and taproot length was between 0.6 to 0.9 m (Figure 4.41). Figure 4.42 indicates that there are outliers on the lower end of the shoot mass.

There was no significant interaction between fire histories and locations on taproot mass. The significant difference existed between locations and between burning histories (*p*= 0.002 & 0.012) (Figures 4.43 & 4.44). Recent burning increased taproot mass probably as a measure of withstanding fire stress.

The interaction between locations and burning histories was not significant for both taproot diameter and length. Significant difference on taproot diameter existed between burning histories, while on taproot depth a weak significance was detected between locations (Figures 4.45 & 4.46). The p-values from the post-hoc tests are indicated in red in Table 4.25 & 4.26.

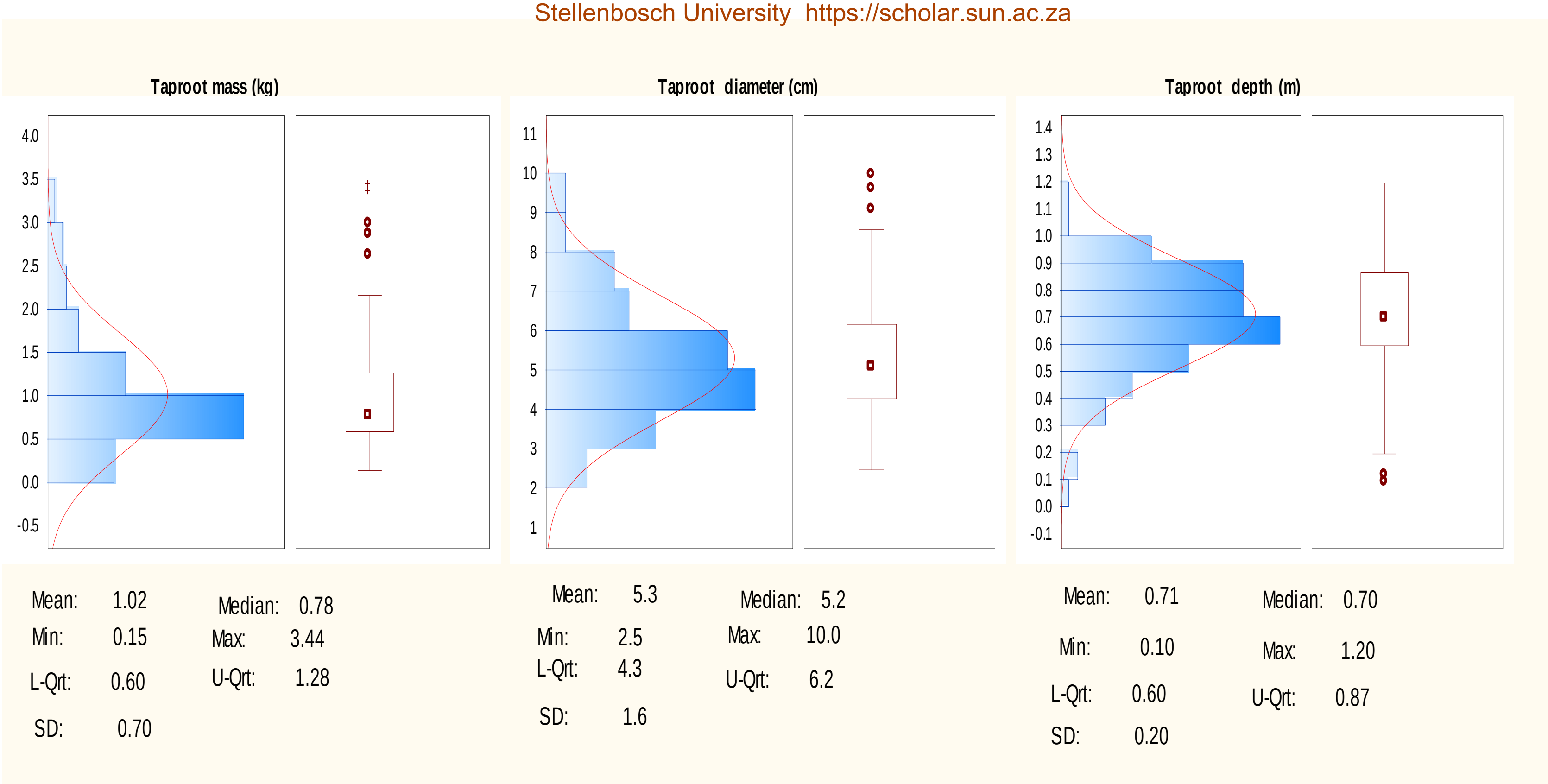


Figure 0.53: Descriptive statistics of taproot parameters of saplings

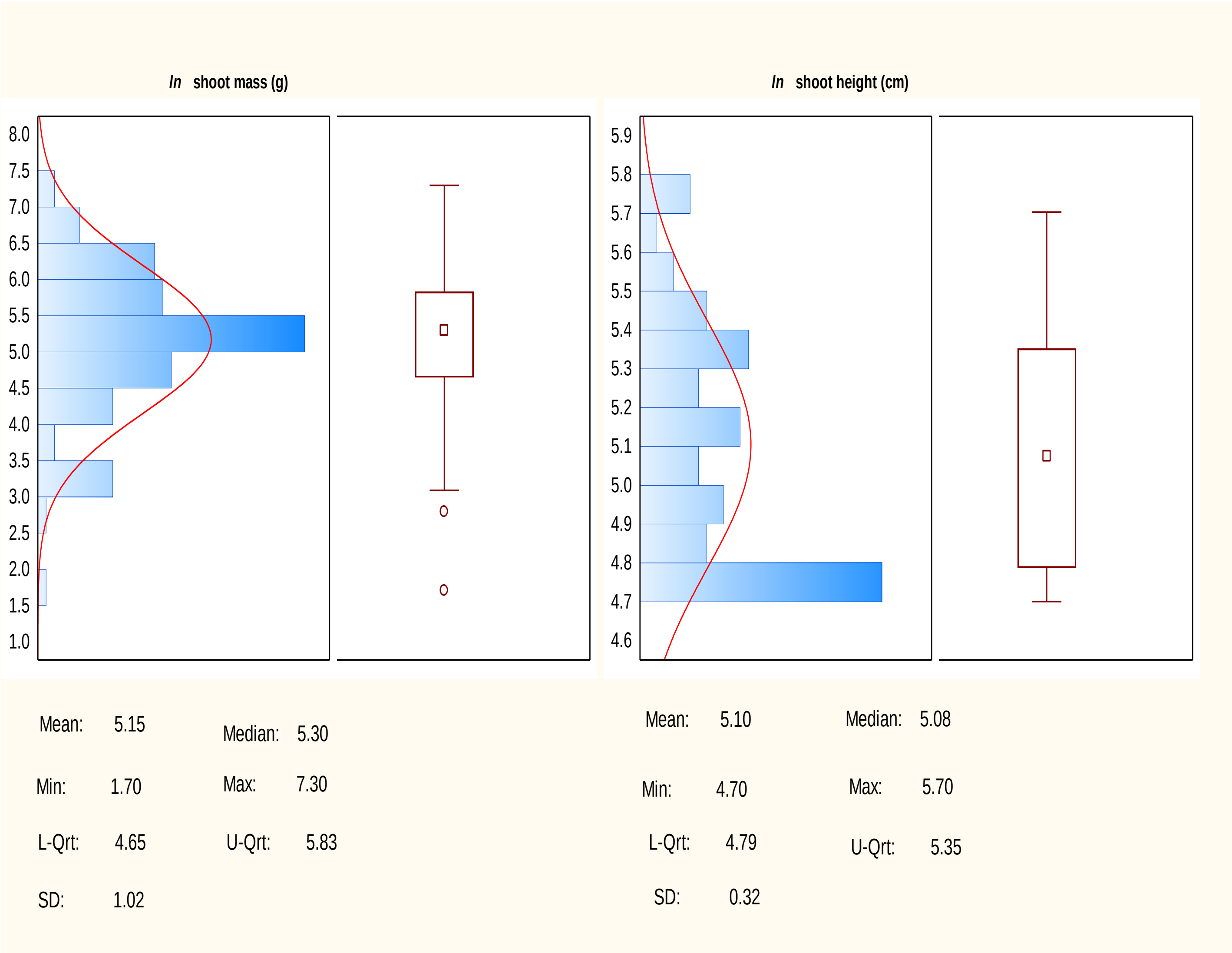


Figure 0.54: Descriptive statistics of shoot parameters of saplings

Table 0.25: Showing tree parts variables increments from seedlings to saplings

	Tree stages		
Tree parts variables	Seedling mean	Sapling mean	Increase in saplings (%)
Taproot mass (kg)	0.72	1.02	41.7
Taproot diameter (cm)	4.8	5.3	10.4
Taproot length (m)	0.72	0.71	-1.4
ln shoot mass	3.15	5.15	
Shoot mass (g)	23.2	172.4	639
ln shoot height	4.23	5.1	

Shoot height (cm)	68.7	164.0	139

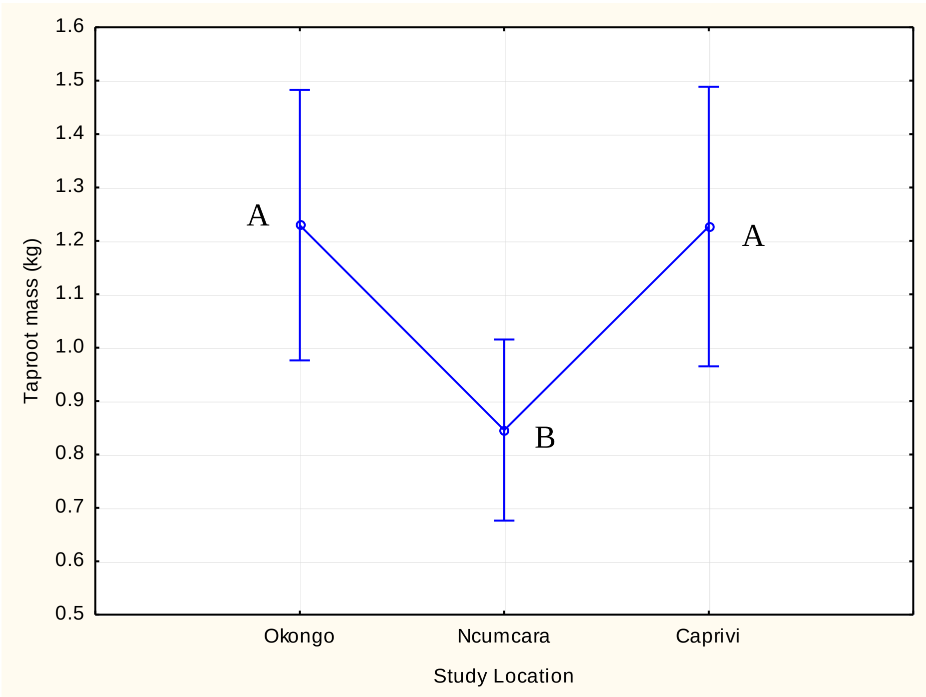


Figure 0.55: Differences of taproot mass of saplings between study locations. Locations with the same letter are not significantly different.

Table 0.26: Multiple comparison tests (Fisher's LSD) for taproot mass of saplings

Study Location	Okongo	Ncumcara
Ncumcara	0.010	
Caprivi	0.590	0.003

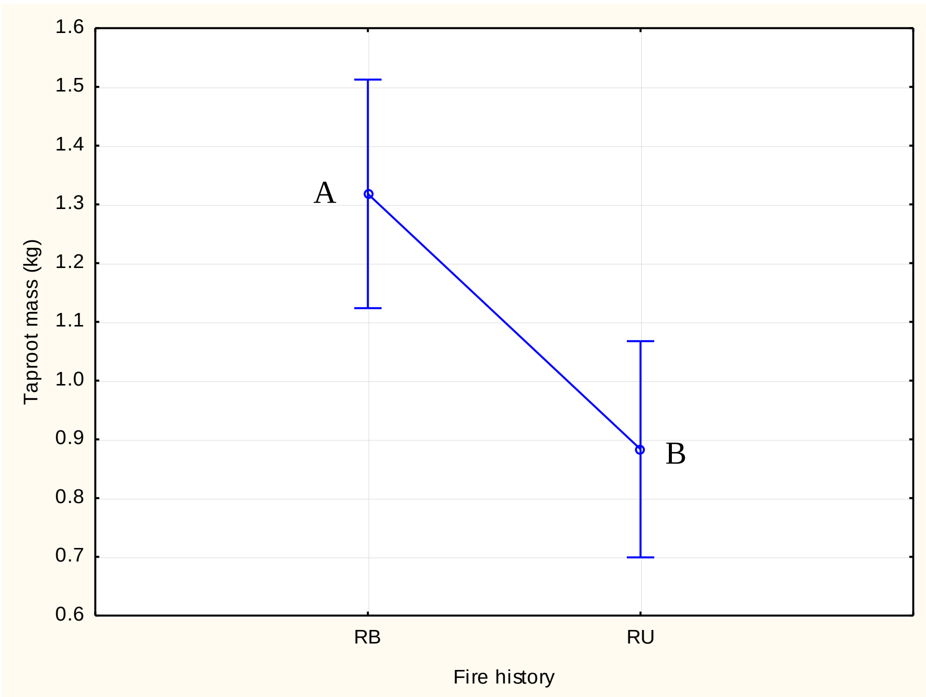


Figure 0.56: Differences of taproot mass of saplings between fire history treatments.

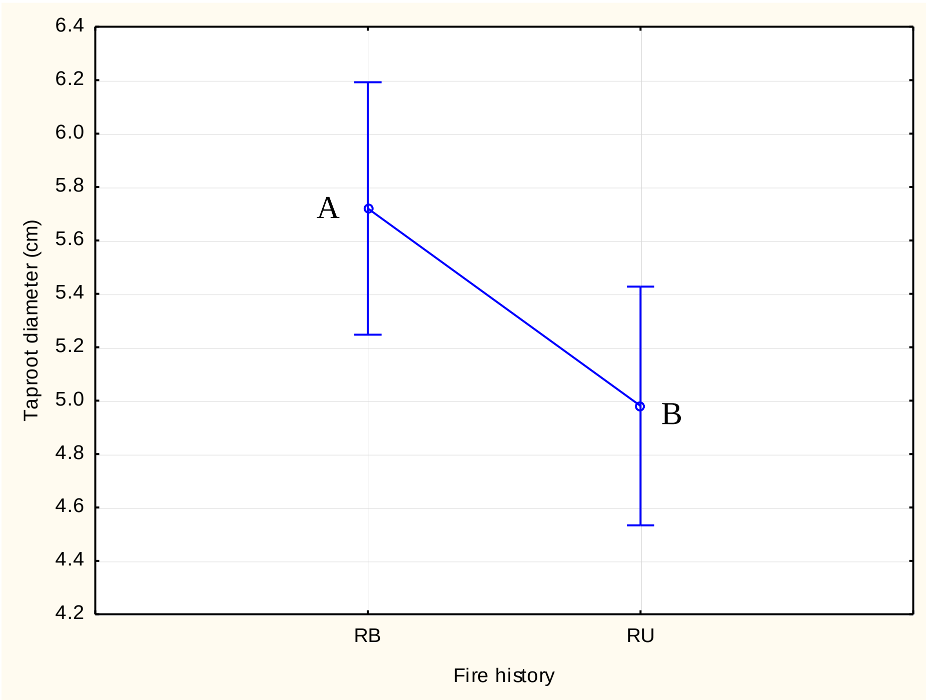


Figure 0.57: Differences of taproot diameter of saplings between fire history treatments.

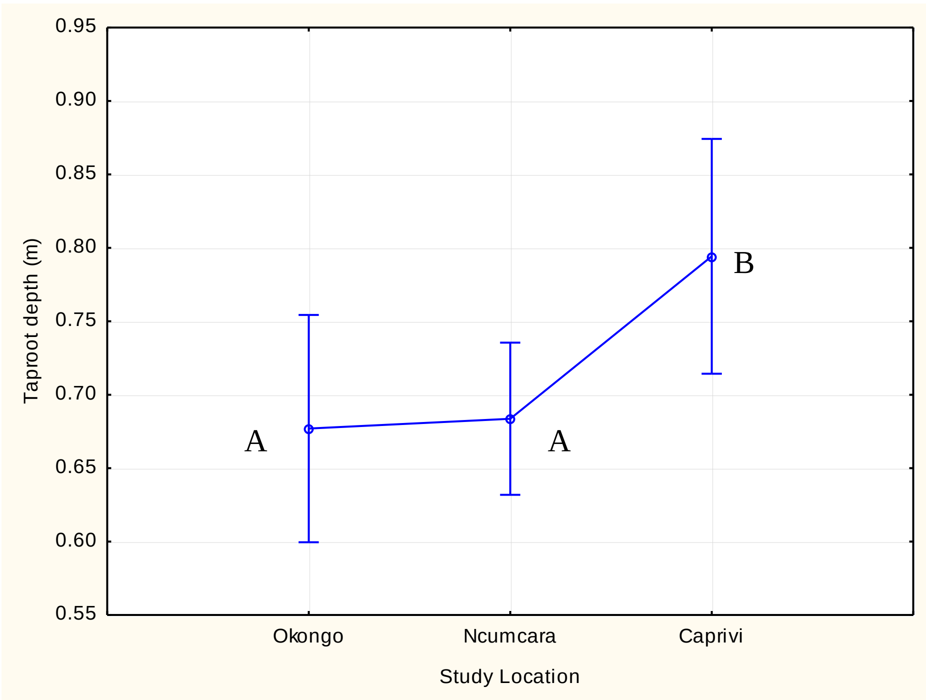


Figure 0.58: Differences of taproot depth of saplings between study locations. Locations with the same letter are not significantly different.

Table 0.27: Multiple comparison tests (Fisher's LSD) for taproot length of saplings

Study Location	Okongo	Ncumcara
Ncumcara	0.871	
Caprivi	0.019	0.005

4.7.2.2 Shoot variables

Shoot mass and height were statistically tested to determine if there are statistical differences between study locations, fire history treatments and interaction of study locations with fire history treatments. This section highlights the analysed results. There is no interaction between locations and fire histories on shoot mass and height, as a result proceeded to interpret the main effects. Again, the shoot mass difference between locations as well as between burning histories was not significant. Only the shoot height showed very weak significant difference (p = 0.071) between fire histories (Figure 4.47**)**. The interaction between locations and fire history treatments on shoot mass as a percentage of taproots mass is weakly significant. The highest shoot mass percentage is visible on the combinations of Ncumcara and RU treatments (Figure 4.48 & Table 4.27).

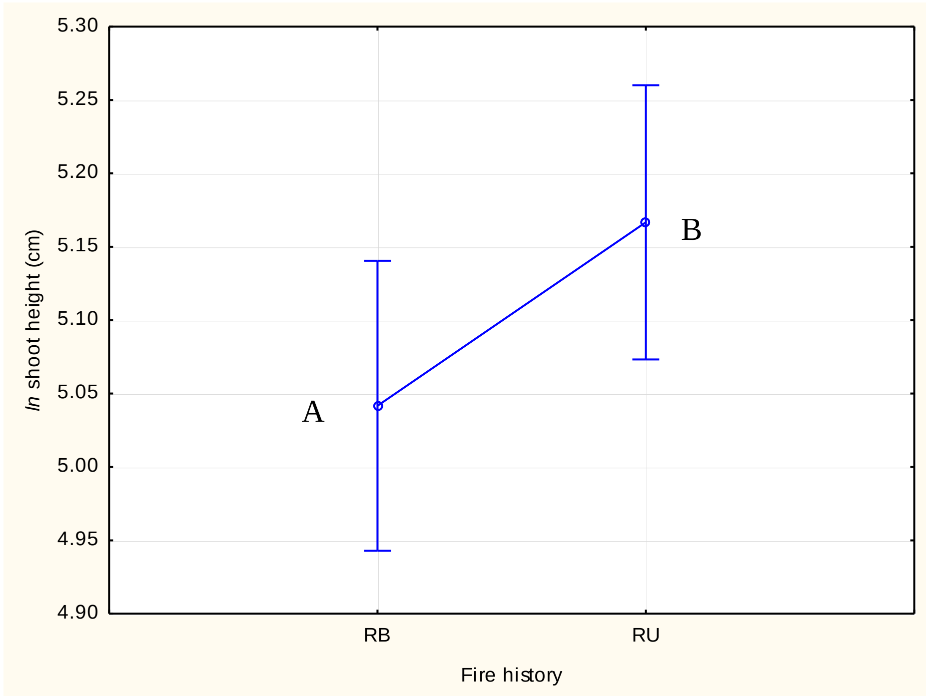


Figure 0.59: Differences of *ln* shoot height between fire history treatments.

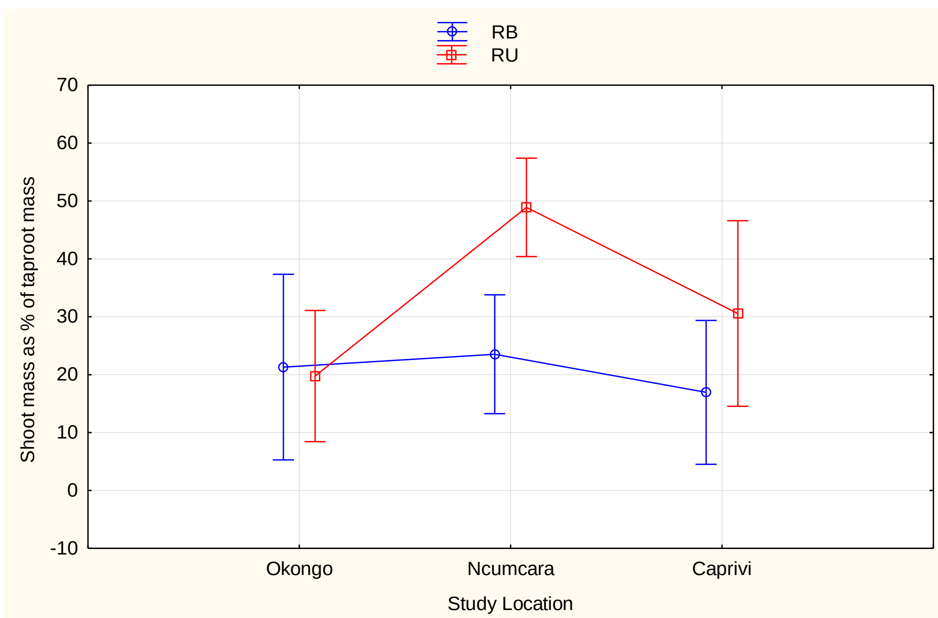


Figure 0.60: The interaction of study locations and fire histories on shoot mass as percentage of taproot mass of saplings.

Table 0.28: Multiple comparison tests (Fisher's LSD) on shoot mass as percentage of taproot mass of saplings

Study Location & fire history	Okongo RB	Okongo RU	Ncumcara RB	Ncumcara RU	Caprivi RB
Okongo RB	0.876				
Ncumcara RB	0.817	0.626			
Ncumcara RU	0.003	<0.001	<0.001		
Caprivi RB	0.670	0.740	0.419	<0.001	
Caprivi RU	0.419	0.277	0.464	0.047	0.185

4.7.2.3 Non-structural carbohydrates (NSC) storage

Sugars and starch (NSC) were analysed to investigate if there was significant difference between locations and between fire history treatments (raw data in Appendix 8). As in previous sections logarithmic scale transformation was performed on non-structural carbohydrate storage data sets. Figure 4.49 shows similar mean for both oligosaccharides and polysaccharides and high mean of starch. There was evidence of outliers in all the datasets. There was no significant interaction between locations and burning histories for all the non-structural carbohydrates storage compounds.

The main effects analysis indicated differences on oligosaccharide and polysaccharide content were significant between locations and between burning histories (Figures 4.50 - 4.53**)**. The starch content was only significantly different between fire history treatments **(**Figure 4.54**)**. Tables 4.28 & 4.29 present the p-values from the post-hoc tests.

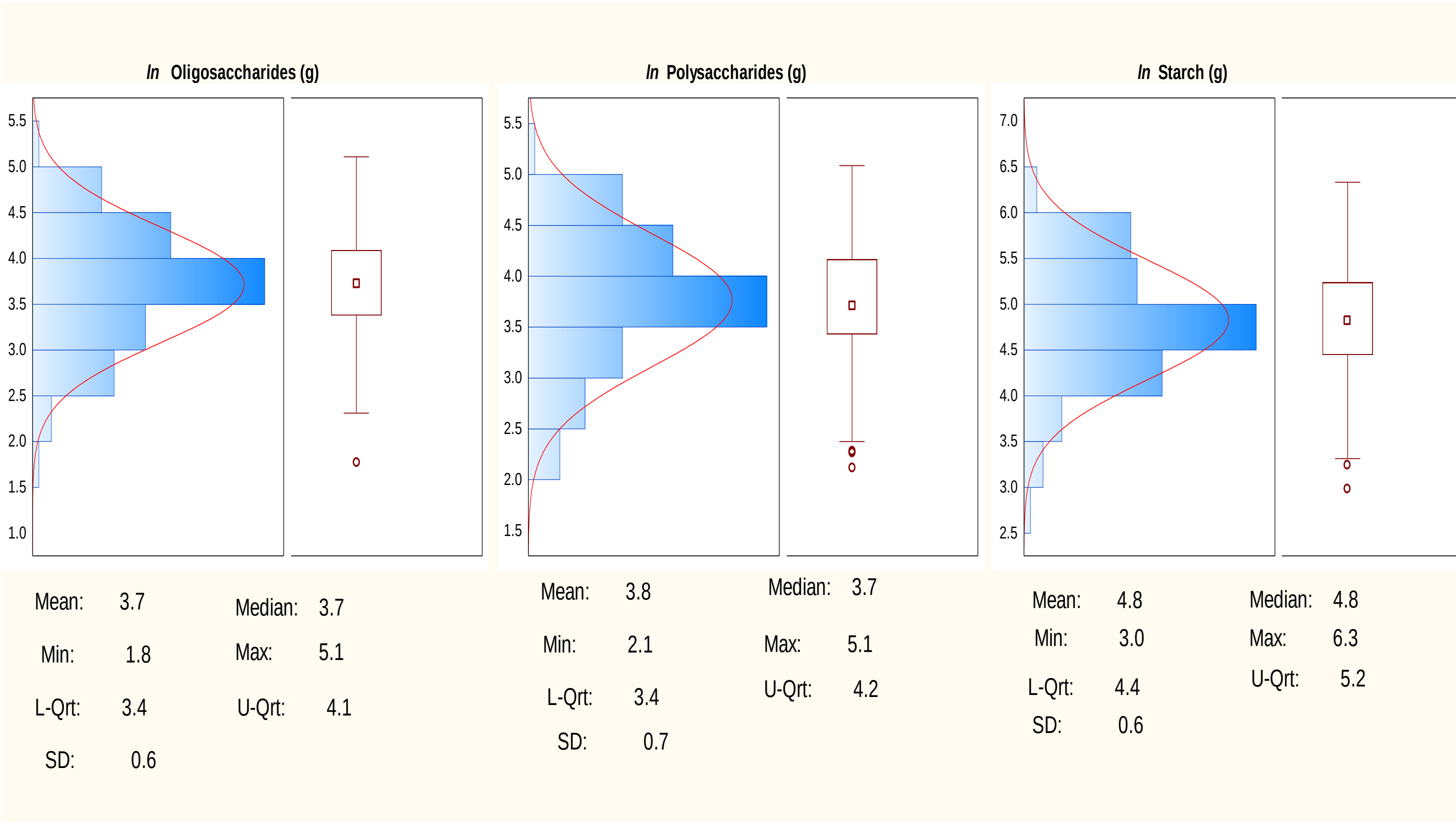


Figure 0.61: Descriptive statistics of non-structural carbohydrates storage of sapling taproots

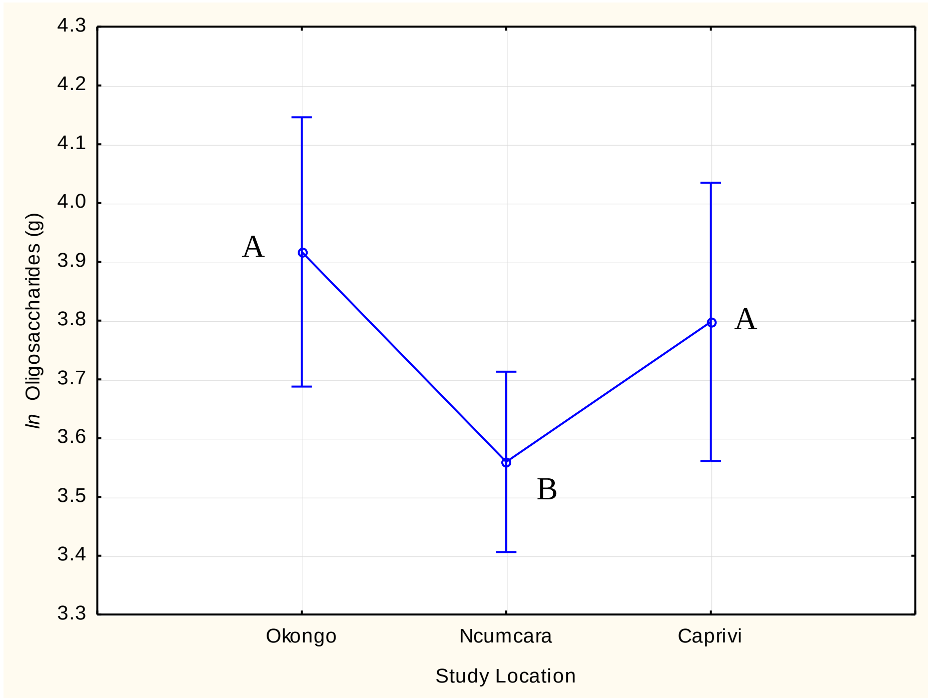


Figure 0.62: Differences of *ln* oligosaccharide content of sapling taproots between study locations. Locations with the same letter are not significantly different.

Table 0.29: Multiple comparison tests (Fisher's LSD) for *ln* oligosaccharides of sapling taproots

Study Location	Okongo	Ncumcara
Ncumcara	0.018	
Caprivi	0.899	0.016

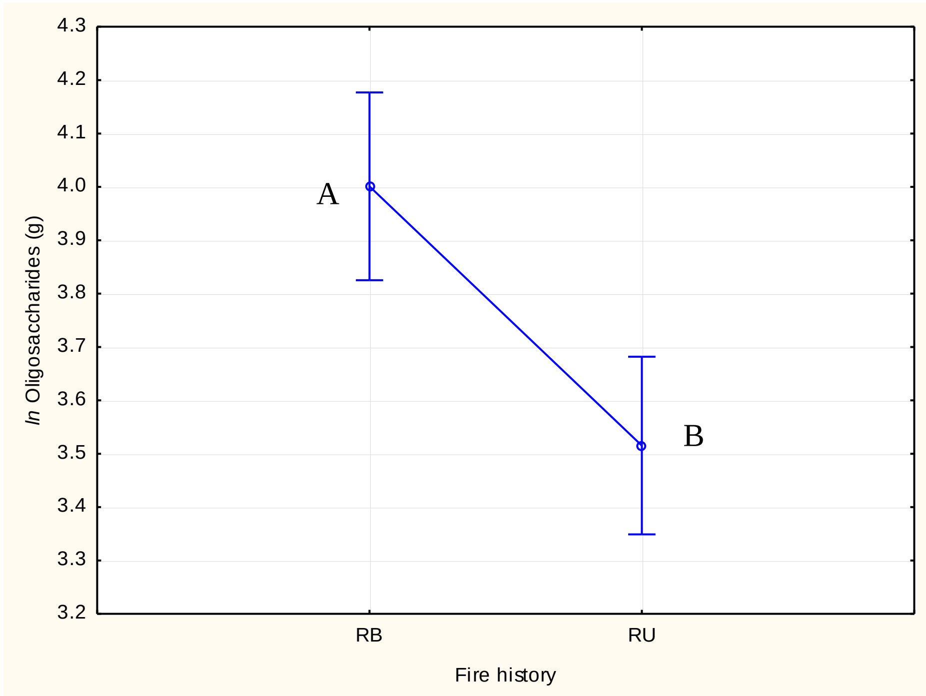


Figure 0.63: Differences of *ln* oligosaccharide content of saplings between fire histories.

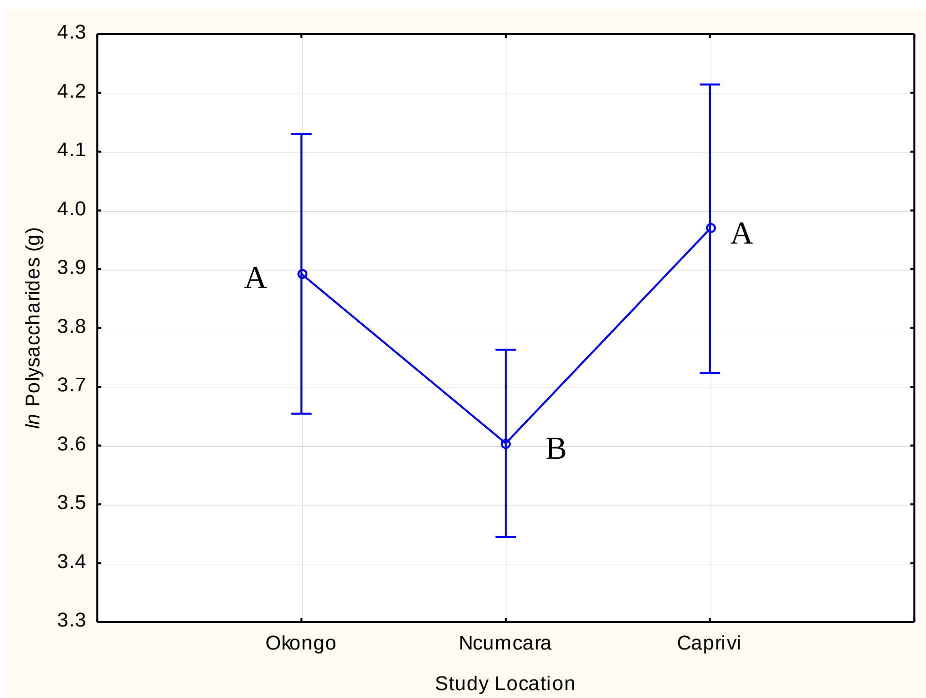


Figure 0.64: Differences of *ln* polysaccharide contents of saplings between study locations. Locations with the same letter are not significantly different.

Table 0.30: Multiple comparison tests (Fisher's LSD) for *ln* polysaccharide content of sapling taproots.

Study Location	Okongo	Ncumcara
Ncumcara	0.024	
Caprivi	0.443	0.003

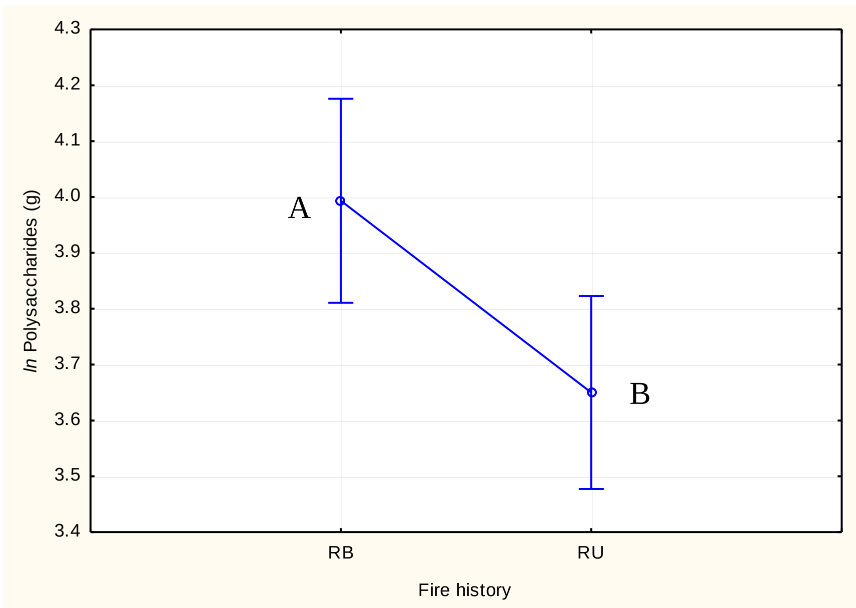


Figure 0.65: Differences of *ln* Polysaccharide contents of saplings between fire histories.

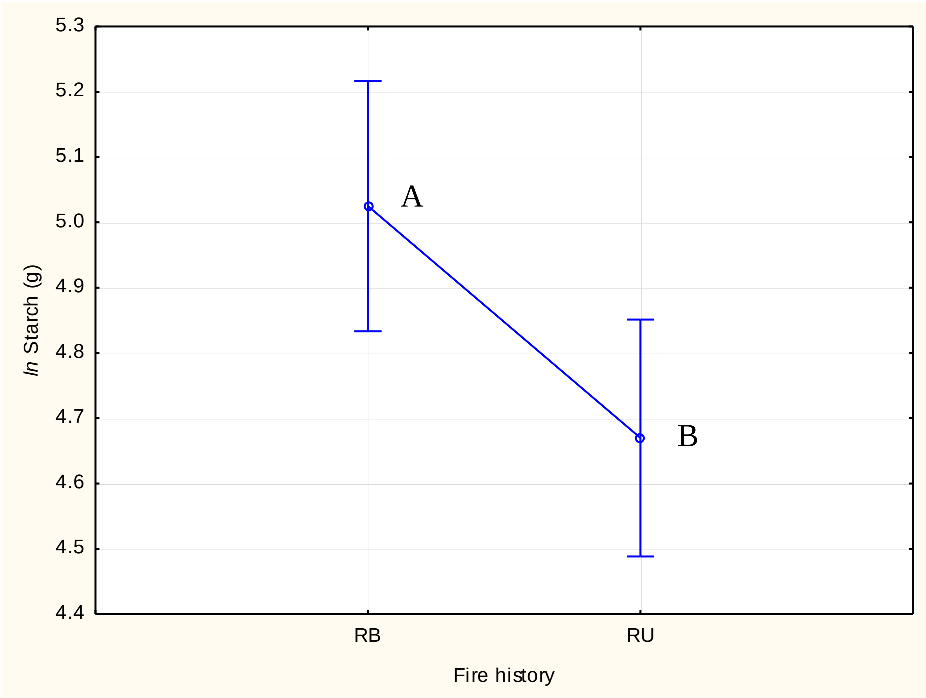


Figure 0.66: Differences of *ln* starch contents of saplings between fire histories.

4.7.2.4 Relationship of taproot variables

There was a good linear relationship between taproot diameter and taproot mass ($p < 0.001$) with correlation coefficient (R) = 0.65 while the coefficient of determination (R^2) = 0.43. The correlation coefficient of 0.66 indicates a positive correlation of the relationship between taproot diameter and mass (Figure 4.55). Taproot mass increases as the taproot diameter increases. If the taproot diameter is increased by one unit, the taproot mass is estimated on average to increase by 0.30 kg (Table 4.30). The coefficient of determination of 0.43 means 43% of the variation in taproot diameter can be explained by the variation in taproot mass. The non-correlation coefficient was noticed between taproot mass and length and showed very poor fitting line.

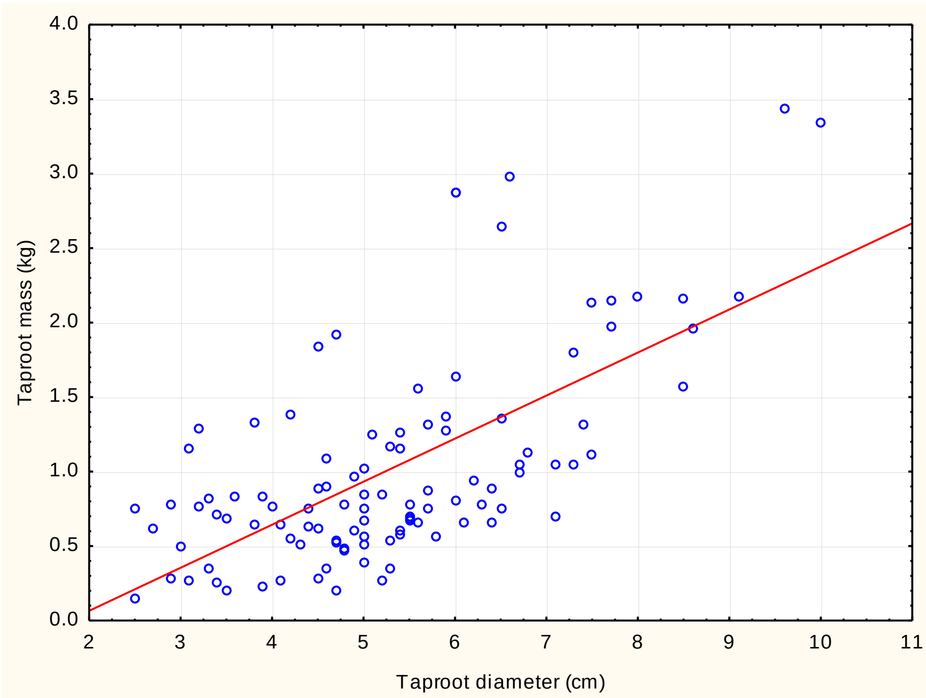


Figure 0.67: The relationship between taproot diameter and taproot mass.

Table 0.31: Linear regression output to determine the effect of taproot diameter on taproot mass; R= 0.65, R^2= 0.43, Adjusted R^2= 0.42

	b*	Std.Err. of b*	b	Std.Err.of b	t(104)	p-value
Intercept			-0.512	0.181	-2.827	0.006
Taproot diameter (cm)	0.655	0.074	0.289	0.033	8.840	<0.001

4.7.2.5 Relationship taproot mass and shoot variables

The statistical analysis on the correlation between taproot mass and shoot mass and height is provided in this section. There was very weak evidence of relationship between taproot mass and shoot mass and height. The very weak relationship existed between shoot mass and taproot mass is presented with correlation coefficient (R) = 0.34 while coefficient of determination (R^2) = 0.12. Correlation coefficient of 0.34 presents a positive correlation of the relationship between shoot mass and taproot mass.

The coefficient of determination of 0.12 means only 12 % of the variations in shoot mass can be explained by the variation in taproot mass that shows weak positive effect. The correlation coefficient and coefficient of determination are presented in Tables 4.31 & 4.32.

Table 0.32: Linear regression output to determine the effect of taproot mass on *ln* shoot mass; R= 0.34, R^2= 0.12, Adjusted R^2= 0.11

	b*	Std.Err.of b*	b	Std.Err.of b	t(104)	p-value
Intercept			4.640	0.166	27.952	<0.001
Taproot mass (kg)	0.343	0.092	0.500	0.134	3.722	<0.001

Table 0.33: Linear regression output to determine the effect of taproot mass on *ln* shoot height; R= 0.11, R^2= 0.01, Adjusted R^2= 0.003

	b*	Std.Err.of b*	b	Std.Err.of b	t(104)	p-value
Intercept			0.134	0.043	3.144	0.002
Taproot mass (kg)	0.344	0.092	0.129	0.035	3.742	<0.001

4.7.2.6 Relationship of non-structural carbohydrate (NSC) storage with taproot variables

The relationship of non-structural carbohydrates storage with taproot mass is seen as important for the growth and sprouting of *Pterocarpus angolensis* development. So, this relationship was analysed and the results presented below. Like the seedlings, for saplings all sugars (oligosaccharides, polysaccharides) and starch had significant effects and strong correlation relationship with taproot mass (Figures 4.56 & 4.58). A strong positive correlation of the relationship between taproot mass and sugars and starch indicated by the correlation coefficient of 0.79 – 0.86. Coefficient of determination of 0.63 – 0.74 was the evidence of good fitted line. The reason for the strong correlation is detailed in section 4.13. If the taproot mass increases by one unit the oligosaccharides is estimated to increase on average by 2.2 g, taproot mass increases by one unit polysaccharides increases on average by 2.2 g while for every unit increase on taproot mass starch increases by 2.1 g (Tables 4.33 – 4.35). The increase on average of all the non-structural carbohydrates storage are almost similar meaning the taproot mass equally affect sugar and starch.

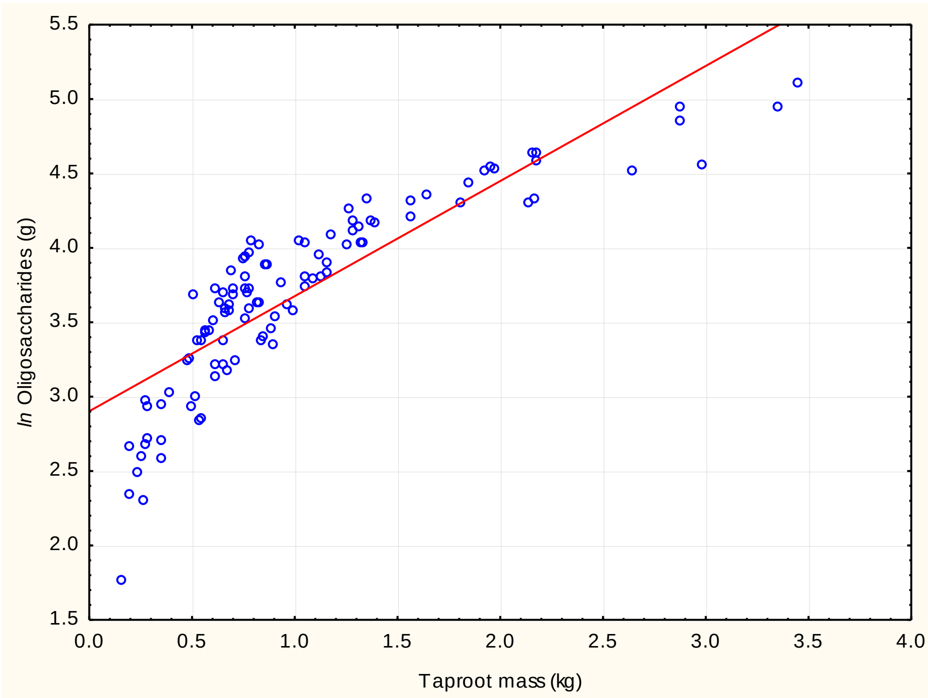


Figure 0.68: The relationship between taproot mass and *ln* oligosaccharide content

Table 0.34: Linear regression output to determine the effect of taproot mass on *ln* oligosaccharide content; R= 0.86, R^2= 0.74, Adjusted R^2= 0.74

	b*	Std.Err.of b*	b	Std.Err.of b	t(104)	p-value
Intercept			2.902	0.056	52.167	<0.001
Taproot mass (kg)	0.860	0.050	0.774	0.045	17.198	<0.001

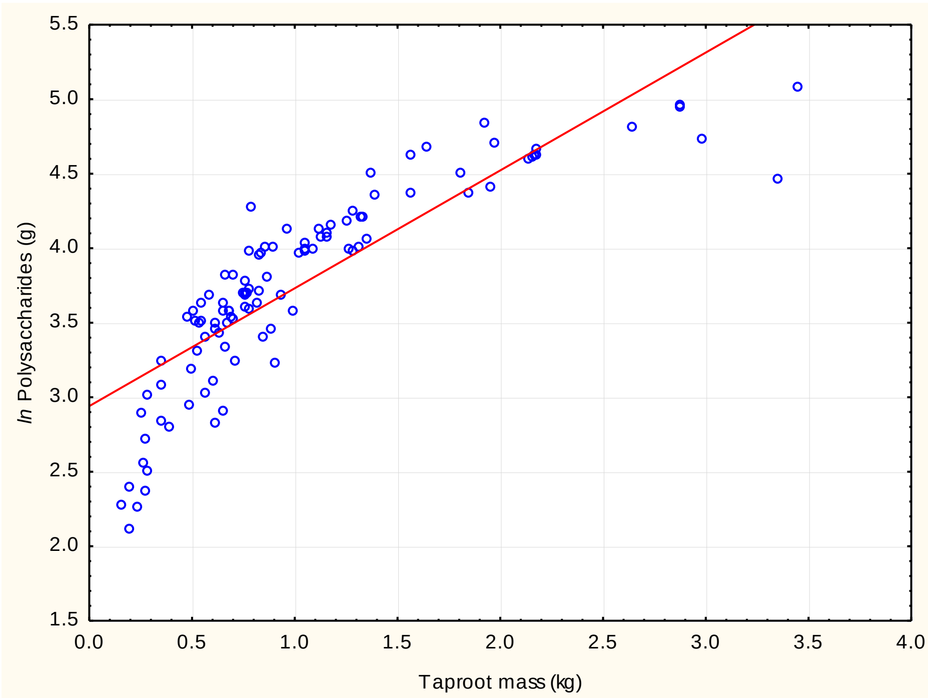


Figure 0.69: The relationship between taproot mass and *ln* polysaccharide content.

Table 0.35: Linear regression output to determine the effect of taproot mass on *ln* polysaccharide content; R= 0.85, R^2= 0.72, Adjusted R^2= 0.72

	b*	Std.Err.of b*	b	Std.Err.of b	t(104)	p-value
Intercept			2.940	0.060	48.965	<0.001
Taproot mass (kg)	0.848	0.052	0.791	0.049	16.285	<0.001

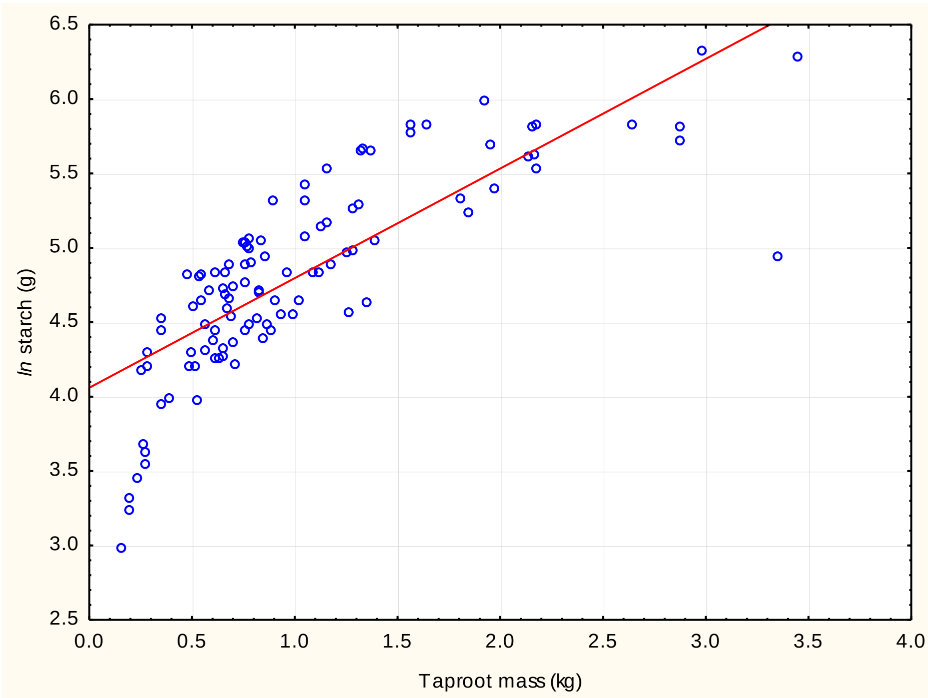


Figure 0.70: The relationship between taproot mass and *ln* starch content.

Table 0.36: Linear regression output to determine the effect of taproot mass on *ln* starch content. R= 0.79, R^2= 0.63, Adjusted R^2= 0.62

	b*	Std.Err.of b*	b	Std.Err. of b	t(104)	p-value
Intercept			4.060	0.069	59.092	<0.001
Taproot mass (kg)	0.793	0.060	0.737	0.056	13.263	<0.001

4.7.2.7 Relationship of non-structural carbohydrate storage with shoot variables

The shoot mass and height relationship with taproot sugars and starch was statistically analysed and presented in this section. There is no good relationship between sugars and starch with *ln* shoot mass and height and the effects of non-structural carbohydrates storage are highlighted in

Tables 4.36 – 4.38**.** The effects of shoot variables in the Tables 4.36 – 4.38 are indicated significant but cannot be used to predict sugars and starch due to non-good relationship.

Table 0.37: Linear regression output to determine the effect of shoot mass on *ln* oligosaccharides content; R= 0.30, R^2= 0.10, Adjusted R^2= 0.10

	b*	Std.Err.of b*	b	Std.Err.of b	t(104)	p-value
Intercept			2.749	0.303	9.060	<0.001
ln shoot mass (g)	0.297	0.094	0.184	0.058	3.176	0.002

Table 0.38: Linear regression output to determine the effect of shoot mass on *ln* Polysaccharides content. R= 0.36, R^2= 0.13, Adjusted R^2= 0.12

	b*	Std.Err.of b*	b	Std.Err.of b	t(104)	p-value
Intercept			2.575	0.308	8.361	<0.001
ln shoot mass (g)	0.356	0.092	0.228	0.059	3.887	<0.001

Table 0.39: Linear regression output to determine the effect of shoot mass on *ln* Starch content; R= 0.36, R^2= 0.13, Adjusted R^2= 0.12

	b*	Std.Err.of b*	b	Std.Err.of b	t(104)	p-value
Intercept			3.623	0.306	11.839	<0.001
ln shoot mass (g)	0.363	0.091	0.231	0.058	3.968	<0.001

4.7.2.8 Tree growth rings counts

In order to estimate the age of a tree, growth ring count was performed on saplings and the results analysed to determine if there is a significant difference between study locations and between fire history treatments. The mean tree growth rings in saplings were 8 and most of the growth ring counts ranged between 5 and 12 with the mean and median almost coinciding (Figure 4.59). As already observed in seedlings there is no significant interaction between locations and burning histories for growth rings in saplings. The difference of growth rings between locations and between burning history treatments was also not significant.

Figure 4.60 highlights the fact that growth ring counts of between 5 and 12 usually have sugars masses of between 0 – 100 g while the same range of growth rings contain mostly starch masses of 100 g and more. Figure 4.61 depicts conspicuous, distinctive vessels and parenchyma cells used to mark ring boundaries.

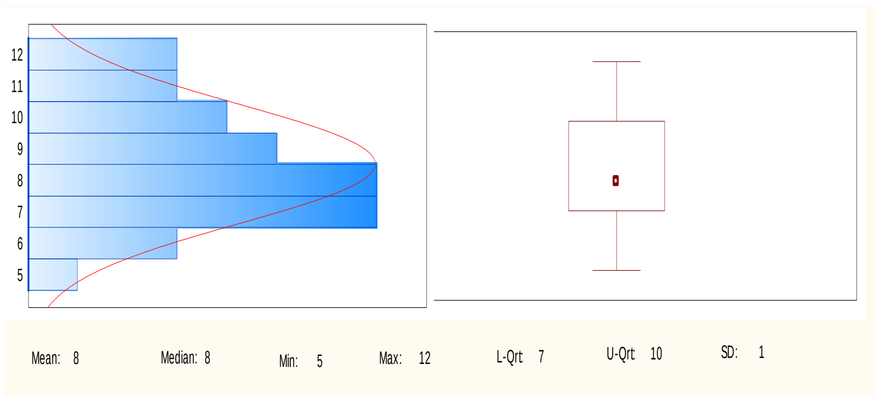


Figure 0.71: Descriptive statistics of tree growth ring count of the saplings

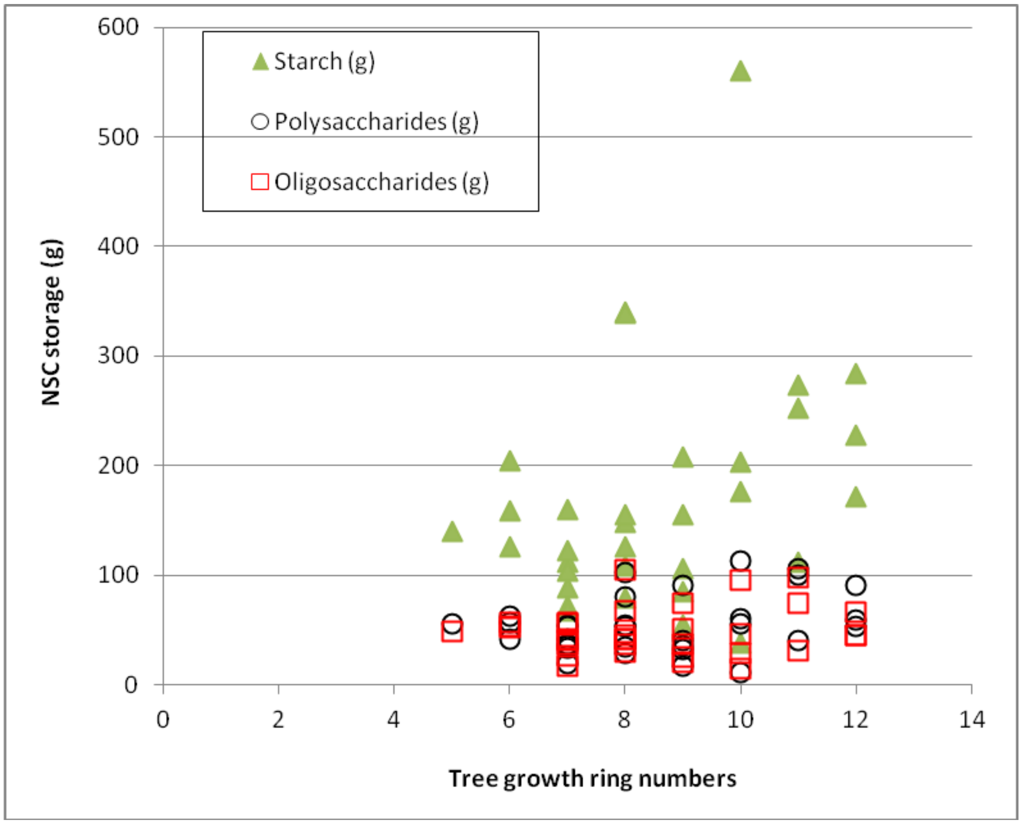


Figure 0.72: The relationship between tree growth rings and non-structural carbohydrates storage of sapling taproots

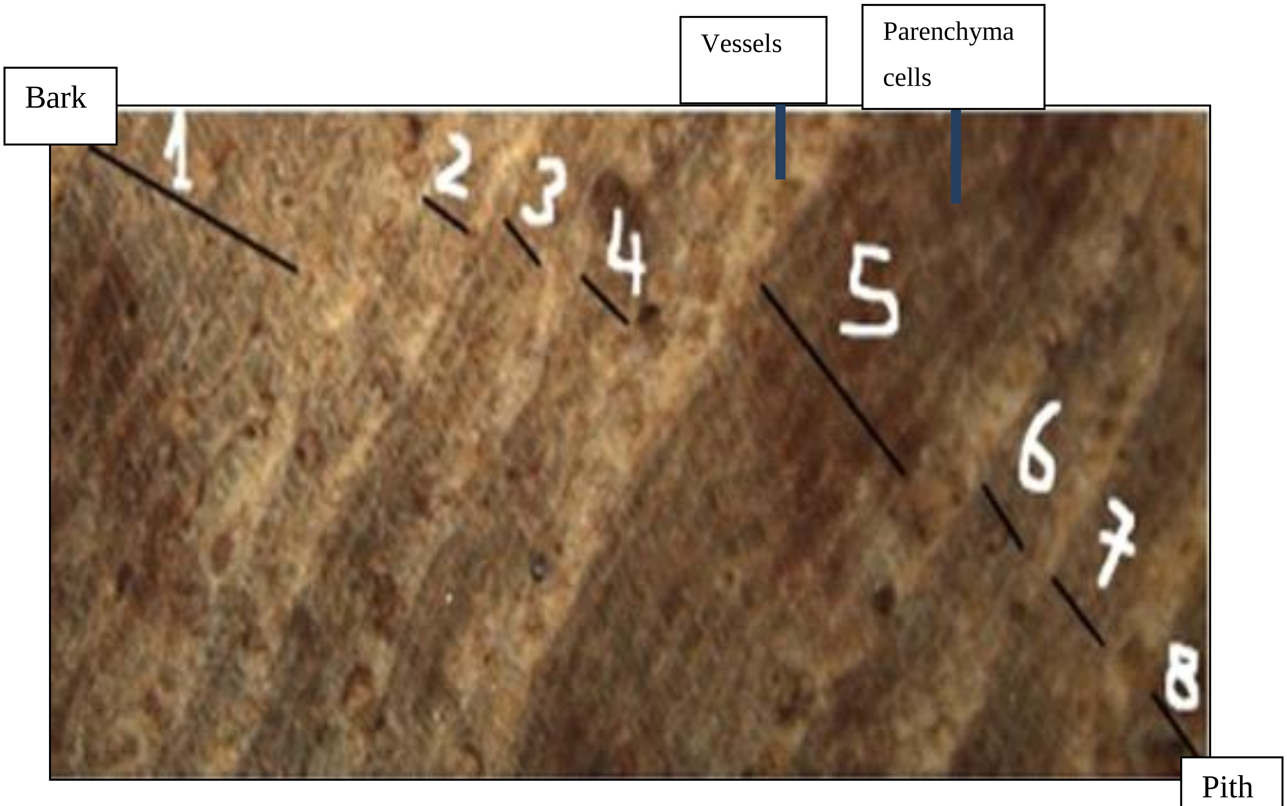


Figure 0.73: Microscopic (x8) image of the cross-sectional surface of a taproot neck disc with black lines showing growth ring boundaries. Parenchyma cells are evident between rows of vessels that indicate growth ring numbers (white numbers).

5.8 Tree damage and stand disturbances

During collecting of data in the field possible disturbances on *Pterocarpus angolensis* growth observed were fires, insects, diseases, drought, animals and human beings (Figure 4.62). Due to these disturbances trees were observed dead with burnt scars on stems and shoots as well as rotten stem parts. Among the observations were dry and dead shoots, taproots with their sides damaged and some stems and branches were observed had been debarked, defoliated, bent and cut. It was observed that 11 % of the total trees inventoried were negatively affected by the disturbances in all three locations, Okongo and Ncumcara 5 % each and Caprivi 1 %. Altogether, 10.2 % of trees in recently burnt treatments were observed affected Okongo 6 %, Ncumcara 4 % and Caprivi 0.2 %. In recently unburnt treatments trees affected were 14 % (Okongo 3 %, Ncumcara 8 % and Caprivi 3 %.).

The main causes of disturbance are presented (as percentage of all the affected trees), in Table 4.39. The main disturbances observed in recently burnt treatments at Okongo were fires 67 % while in recently unburnt treatments was drought (dried stems & shoots) 86 %. At Ncumcara in recently burnt treatments the major disturbances observed was also fires 71 % while in recently unburnt treatments was human being 82 %. Disturbance observed in recently burnt treatments at Caprivi was only fires while recently unburnt treatments were human being and insects (Table 4.39).

Table 0.40: Percentages of trees of the total affected trees by different disturbances per study location and per fire history.

	Okongo		**Ncumcara**		**Caprivi**	
	Trees (%)		**Trees (%)**		**Trees (%)**	
Disturbances	Recently burnt	Recently unburnt	Recently burnt	Recently unburnt	Recently burnt	Recently unburnt
Fires	67	14	71	0	100	50
Human beings	0	0	0	82	0	0
Drought	9	86	0	0	0	0
Animals	8	0	0	18	0	0
Insects	8	0	29	0	0	50
Diseases	8	0	0	0	0	0

Dead tree bole (fires or diseases) Damaged taproot (insects or diseases)

Figure 0.74: *Pterocarpus angolensis* bole and taproot negatively affected by disturbances

Summary

The survey results provide information that most of the community members in the three locations are aware of some factors influencing the development of *Pterocarpus angolensis*. However, there was no evidence of silvicultural practices being implemented by the community to enhance *Pterocarpus angolensis* development. The results confirm that the three locations soil structure is mainly dominated by sandy soil.

All the three locations have growing seedlings, saplings and mature trees with different stocking, basal area and DBH. In addition, the results show that taproots store large quantities of non-structural carbohydrates as starch, as well as sizable quantities in the form of different types of sugars (oligosaccharides and polysaccharides).

Cross-dating performed estimates the age of seedlings and saplings by counting the number of growth rings that show non-significant difference between locations and fire history treatments. The results presented in Chapter 4 are discussed in detail in Chapter 5. The discussion is mainly focusing on interpretation of data in relation to previous findings as well as in reference to the study problem statement.

Chapter 5: Discussion

5.1 Introduction

Chapter 5 discusses results as presented in Chapter 4. The discussion includes: (1) interview survey; (2) soil characteristics and climatic information; (3) tree growth by development stages; (4) tree population size class distribution; and (5) factors affecting *Pterocarpus angolensis* development. The findings obtained through interviewing community members and forestry officials are used to assist in explaining phenomena that we have observed in population data sets, destructive harvesting and laboratory analysis. Discussion also focuses on the relationship between this research findings and findings in literature.

5.2 Interview survey

The majority of the respondents were males of 30 – 50 years old who are mainly farmers. Most of these farmers are from Okongo Community Forest surroundings, meaning Okongo recorded more farmers interviewed compared to Ncumcara Community Forest and Caprivi State Forest. This is an indication that there are a lot of agricultural activities being carried out in the area of Okongo Community Forest. Many of the village heads are more than 50 years old and have in-depth indigenous knowledge on *Pterocarpus angolensis* tree development. The carpenters were only interviewed at Okongo and Ncumcara because there were no legal harvesters encountered in the Caprivi State Forest area during the interview period. Furthermore, Caprivi State Forest is under State management and tree harvesting is very restricted, while Okongo and Ncumcara Community Forests are under Forest Management Committees whereby tree harvesting is permitted in a sustainable manner. The results of the answers to the questionnaire will be discussed together with empirical data from our inventory and destructive sampling campaigns in the sections that follow.

5.3 Soil characteristics and climatic information

Graz (1996) states in Southern African woodlands *Pterocarpus angolensis* is found in a well-drained soil, white-yellow sand, Kalahari sands, low foothills and red sand. The soil analysis confirms that the soil texture in the three study locations is dominated by sand and that soils have an acidic soil reaction (Table 4.7). These soil properties are common for forest soils where *Pterocarpus angolensis* occurs.

According to Takawira-Nyenya (2008), *Pterocarpus angolensis* requires well-drained, medium to light soils of low to moderate fertility and pH 5.5–7. The listed pH KCl is a little bit higher than the salt pH of between 4.2 to 5.4 found in the three study locations. Note that the pH reported in this thesis was measured in the standard 1M KCl solution and is this expected to be slightly lower than any water pH that has been recorded in the literature. The pH in recently burnt treatments range from 4.6 to 5.4 in KCl while that of recently unburnt treatments range from 4.2 to 4.7 in KCl. It is common for the topsoil pH to increase for a period after fire, due to the presence of the alkaline ash washing in from the soil surface. This effect had been described for several forest systems in the months following fires (Fisher & Binkley 2000).

The recently burnt treatments also have the highest plant-available phosphorus and ECEC. The former is likely to be due to the decrease in acidity and its effect on sparingly soluble Fe and Al phosphates, while the latter is probably due to the effect of variable charge being converted to cation exchange sites with increasing pH. Temporary increases in ECEC have also been observed after fires in eucalypt plantations in South Africa (du Toit *et al*., 2008). The study by Mehl *et al.* (2010) revealed that a phosphorus level is low in the Miombo soils because of the annual fires burning organic matter. Plant-available phosphorus levels may be low by agricultural standards; however, the levels of P are much higher than those in more acid forestry soils of high rainfall areas (du Toit *et al*, 2008; Fey, 2010). This is to be expected because the formation of relatively insoluble Fe and Al phosphates is greater in more acid soils.

The topsoil organic matter content in soils of all the study locations was very low. It is known that extreme acidity, cold and lack of nutrients may retard microbial breakdown of the organic matter, thus leading to a build-up of organic matter in some soils. The low organic matter is due to low water availability to break down organic matter leading to organic matter being blown and burnt by fires before breaking down. Conversely, at high temperatures and only moderately acid conditions (such as our study locations), organic soils does not form as the materials break down too fast (Fey, 2010). It is also known that young aeolian sands are usually low in organic matter (Fey, 2010). The recently burnt soils in Caprivi generally showed the largest values for organic carbon, and water holding capacity but this effect was not significant.

5.4 Tree population size class distribution

5.4.1 Stocking

Study results presented below are obtained from an area of 0.48 ha per plot which is 1.92 ha per fire history treatment and 3.84 ha per location totalling 11.52 ha for the three locations. This section highlights trees found per ha, basal area and DBH and *Pterocarpus angolensis* development stages in the three locations. The details on basal area and DBH are in sections 5.5.2 & 5.5.3. The average stands descriptor values (de-transformed from Figure 4.18) across all the three study locations are as follows: The stocking for *Pterocarpus angolensis* is 133 trees/ha, Basal Area 6.0 m^2/ha and DBH 11.2 cm.

The study by Chingonikaya *et al* (2010) carried out in Miombo Woodland in Tanzania in Mgori forest reserve noted tree basal area from 9.6 m^2 ha^{-1} to 18.5 m^2 ha^{-1}. The basal area from our study is thus notably lower because it does not include other tree species found in the three locations. Stocking is unequally distributed while most of the BA and a fair number of trees have DBH more than the median (Figure 4.18). The bulk of the large diameter trees occur at Okongo.

The low means of DBH and BA at Ncumcara and Caprivi suggested that there are not many big *Pterocarpus angolensis* in these study locations, which might be due to intensive harvesting of big trees in previous years mainly in Ncumcara Community Forest and Caprivi State Forest, a factor also reported by the interviewed respondents.

The stocking confirms the relatively low presence of *Pterocarpus angolensis* trees in the three forests in comparison with other forests in miombo woodland probably because of adverse establishment conditions and competing vegetation. The recruitment of juvenile tree stage into adult tree stage is high in the absence of other vegetation due to little competition. The study by February et al. (2013) found out that trees in plots where grass were removed grew on average height of 15 cm more per year than in plots where grass were not removed. The most abundant tree development stages found by this study is mature trees followed by saplings with seedlings the lowest (Figure 4.18). The fact that the seedlings abundance is low in all three locations may be due to drought, nutrient deficiencies, damage by recent high intensity fires and animals as described by Takawira-Nyenya (2008). However, the number of seedlings shows the ongoing tree recruitment in the forests but the recruitment is low compared to the number of saplings and mature trees in all the study locations.

According to statistical analysis there is no significant interaction between locations and fire history treatments as well as between locations and between fire history treatments on seedlings. This can be translated that different rainfall gradient and fire history treatments in the three locations do not play any significant role on the seedling abundance. The sapling abundance differs between locations and this difference is highly significant (Figure 4.19). This significant difference of sapling abundance between Okongo and Ncumcara and Caprivi might be influenced by higher rainfall in Caprivi and Ncumcara (Figure 3.4). Again, this may mean during the past years most of the seedlings at Okongo with the lowest sapling abundance spent many years in suffrutex stage. Munthali (1999) also states, low natural regeneration is mostly attributed to sensitivity to severe drought and irregular and intermitted rainfall that may possibly have been experienced by Okongo in the past years.

The abundance of mature trees only differs significantly between study locations. The significant difference is between Okongo and Ncumcara and between Okongo and Caprivi but not significant between Ncumcara and Caprivi (Figure 4.20 & Table 4.9). Interestingly, Okongo with lowest rainfall recorded the highest mature tree abundances. Even though many mature *Pterocarpus angolensis* trees discovered in Okongo Community Forest that can produce adequate seeds, seedlings are still sparse like at other two locations.

At all the three study locations Okongo recorded the highest mature trees, Ncumcara the highest saplings and Caprivi the highest seedlings abundances but seedlings abundance differences is not significant. Similarly, most of the respondents (65 %) of Okongo rated mature trees as the dominant size class and at Ncumcara the majority of the respondents (87 %) rated saplings as the most common size class (Figure 4.3). In contrast, at Caprivi a high number of respondents rated saplings as dominant, but field data revealed that mature trees were more abundant than seedlings and saplings. At Okongo and Caprivi the number of mature trees is the highest while at Ncumcara saplings is the highest. The low number of mature trees at Ncumcara and Caprivi compared to Okongo is apparently due to intensive harvesting of mature *Pterocarpus angolensis* trees in the past years (Section 4.2.11).

The low number of saplings at Okongo and Caprivi compared to Ncumcara might be due to previous fires in past years that suppressed recruitment of seedlings to sapling stage. In general, the regeneration of *Pterocarpus angolensis* trees in the three study locations is natural. The majority of the respondents (84 %) confirmed the communities adjacent to the three forests do not perform any silvicultural practices to promote *Pterocarpus angolensis* growth. However, there are several silvicultural practices such as seed treatments, land preparation, removal of competitors, weeding, pruning and thinning that can be implemented to enhance tree growth. On one hand, large quantities of trees are being harvested for sawn timber, carving and carpentry for tourists. This may be viewed as unsustainable, because nothing is done to enhance the growth or abundances of *Pterocarpus angolensis* trees.

5.4.2 Tree DBH and height size class distribution

Trees were grouped based on their DBH and height as illustrated in this section. Across all the study locations many trees are in the 0 – 10 cm DBH class (Figure 4.16). Recently burnt treatments in Ncumcara and Caprivi have higher number of trees across all DBH classes compared to recently unburnt treatments. At Okongo the burning history appears to have very little effect on the number of individuals per DBH class (Figure 4.17). There is low number of trees in the height class of 0 – 0.5 m in both treatments of Okongo and Caprivi but at Ncumcara numbers of trees present in this class is much lower, and only noted in recently burnt treatments.

The fact that height classes 0.6 - 1.0 m and 1.1 – 1.5 m have much higher numbers of individuals than the lowest height class (0 -0.5 m), is a function of the developmental stages of *Pterocarpus angolensis* that is already well documented. After seed germination, young trees take several years to progress through to the seedling and sapling stages, and there is thus an accumulation of individuals in these size classes over time. Each seedling and sapling size class will thus harbour seedlings or saplings that have germinated in many different years (Figures 4.16 & 4.17).

In Ncumcara and Caprivi an increased number of trees are found in recently burnt treatments across all the height classes. The effect of recent fires could explain the larger number of seedlings. It appears that the type of burning done at Ncumcara and Caprivi does open up the forest undergrowth, thus partially eliminating competition and stimulating seedling recruitment. This effect has been described in the literature (Vermeulen, 1990) and also by some respondents to questionnaires contained in this thesis (Section 4.2.11).

However, the increased presence of saplings in size classes above 1.5 m in recently burnt plots must probably be ascribed to unknown conditions that favoured regeneration more than 4 years ago (i.e. it is probably beyond the scope of our fire history treatments). These conditions may have been the non-occurrences of fires or low fire intensities in past years that reduced seedling mortality, but our study did not focus on this aspect.

At Okongo trees are almost evenly distributed (irrespective of burning history) across all the height classes. The similar distribution of trees of both DBH and height classes (inverse J-shape) in Ncumcara and Caprivi is influenced by conditions favourable for regeneration: the relatively high rainfall in those areas plus other factors such as regular, low intensity burning might be also contributing. Conversely, at Okongo the higher number of trees in recently unburnt treatments in height class 0.6 – 1.0 m, 2.1 – 2.5 m and 2.6 – 3.0 m may illustrate seedling and sapling shoots not killed by forest fires for at least the last four years. It is possible that the burning conditions of the fire in the recently burnt treatments at Okongo were not suitable for seedling development. This may be due to a high intensity fire (or fires) in the past, caused by the build-up of fuels over several years (25% of respondents indicated that there are large parts of the Okongo forest that does not burn annually or even bi-annually – see Section 4.2.12).

5.4.3 Saplings and bole trees DBH and BA

This section presents sapling and bole tree DBH and BA which were analysed to determine their differences between the two development stages. The distribution of *Pterocarpus angolensis* tree BA (de-transformed from Figure 4.20) and DBH varies between saplings and bole trees. The high BA and DBH on bole trees compared to saplings is because bole trees have bigger stems than saplings. Therefore, it is expected for saplings to have lower BA than bole trees because saplings are regarded as regrowth while bole tree as old growth.

For saplings the significant difference of BA existed between fire histories treatments in which recently unburnt treatments recorded the highest which means there are large-stemmed saplings in the areas that were not burnt for long time. This also suggested that fire retards growth of sapling stems. In addition, the high BA in the recently unburnt treatments may reduce regeneration of seedlings due to increase of tree canopy cover that may suppress seed germination. It was also predicted that BA of saplings increases with rainfall but the study found out that the locations across a rainfall gradient not having influence on BA as no significant difference observed between locations for both saplings and bole trees. The majority of the respondents (91 %) of all three locations perceived soil water as the most factor influencing *Pterocarpus angolensis* development from sapling to bole tree stage.

Significant differences were observed in DBH between study locations on bole stage trees, Okongo noted the highest because of big mature trees in the forest. Although there was a significant difference between locations on mature trees there was no significant difference between any of the locations, fire history treatments and interaction on BA of bole trees. The higher trends of Ncumcara and Okongo fire history treatment combinations than Caprivi fire history treatment combinations were probably the driving force to this significant interaction on mean DBH of the bole tree. In addition, the highest mean DBH recorded in the combinations of Okongo fire history treatments might be due to high number of mature trees with bigger DBH found at Okongo (Figure 4.24).

5.5 Tree growth by development stages

This study investigated the significance and relationship of taproot and shoot parameters that play important roles in the tree growth and development as well as the relationship between these parameters and non-structural carbohydrates as outlined in this section. Nyondo (2002) states that the die-back of seedling shoots occurs every year until the taproots accumulate adequate food and nutrients, and the root system has grown deep enough to reach soil moisture reserves. The root system (below ground biomass) must grow sufficiently to support the shoot to withstand the dry season (Boaler, 1966). The taproot mass of saplings were 42% greater than that of seedlings, but the taproot diameter only differed by 10% and the depth was effectively similar. In strong contrast, the shoot height of saplings increased by 139% to the sapling stage and the shoot mass increased by 639% (Table 4.24).

The interactions between locations and fire history treatments on seedlings taproot mass were significant (Figure 4.27). This significant interaction on taproot mass was due to high values recorded at the Ncumcara recently burnt treatment combination, and this has two plausible explanations: (a) If the most recent fires were particularly intense (this information is unknown), it may be possible that above ground parts of smaller seedlings were so badly burnt that they did not re-sprout sufficiently to be identified and subsequently sampled. (b) Alternatively, the result could indicate that the taproots have been forced into a prolonged mass and carbohydrate accumulation phase (due to the fire) which enhances the build-up reserves to stimulate shoot growth in future. At Ncumcara seedlings are damaged by browsing and fires which occur every year as indicated by the majority of the questionnaire respondents. Therefore, repeated fire *combined* with preferential browsing after fires when there is little other fodder, may lead to an increased taproot mass as a measure to enable seedlings to survive during dieback periods. The shoot mass was significantly different between locations (Figure 4.29) Ncumcara recorded the highest while Okongo recorded the lowest, with the effect of fire history being insignificant. The reason for this could possibly also be ascribed to intensive browsing of the smaller shoots, but this explanation, although plausible, is less certain.

Figure 4.30 indicates a weakly significant interaction between locations and fire history treatments on shoot mass as a percentage of taproots mass, with a range of 4 – 10 % for seedling size classes. The RU treatments at Ncumcara recorded a higher shoot mass as a percentage of taproots mass, when compared to Okongo and Caprivi, meaning seedlings at Ncumcara use more carbohydrates for shoot growth. Again, this higher shoot mass percentage noted in Ncumcara and RU treatment combinations might be due to a long time without fire in the forest or less competition from other plants.

Taproot parameters for <u>saplings</u> were only significantly different among locations and among fire history treatments (Figures 4.43 – 4.46). The highest sapling taproot mass in recently burnt treatments may be due to burning that made more soil nutrients available for absorption by the taproot (Figure 4.44). Figure 4.48 for <u>saplings</u> indicates that shoot mass as a percentage of taproot mass is weakly significantly greater on the recently unburnt treatment at Ncumcara. This is thus the same trend as for seedlings (Figure 4.30) However, the magnitude of the interaction for saplings in the combination of Ncumcara and RU treatments is larger: it reveals that shoots mass of the saplings as percentage of the taproot mass ranges as high as 20 – 50 %. Therefore, at Ncumcara other factors such as browsing of other plant species that reduces vegetation competition might have more effect on the shoot mass of the saplings. The areas that have been unburnt in recent times have developed a larger shoot mass and this could act as a sink for non-structural carbohydrates from the taproot. This is a likely mechanism whereby sugar and starch contents is accumulated in the taproot during regular fires and mobilized to the shoot when fire is absent for some years.

Again, taproot diameter difference is significant for saplings between fire history treatments whereby recently burnt treatments recorded the highest, confirming that the expansion of the taproot takes place to accommodate more NSC for the tree to survive during fire or drought and facilitate new growth shoots afterwards. Deciduous fire tolerant tree species such as *Pterocarpus angolensis* have high levels of below ground carbohydrates to be able to flush again at the beginning of rain season (Newel et al, 2002; Bond and Midgley, 2003). Caprivi with the high rainfall noted the highest taproot depth, so taproot grows deep to obtain more nutrients. In addition, highest sapling shoot height in recently unburnt treatments was mainly because the area was not burnt for a long time so shoots growth was not retarded (Figure 4.47).

The mean contents of sugars (oligosaccharides and polysaccharides) indicated that the sugars in both seedlings and saplings were the same. The starch mean showed more starch in saplings compared to seedlings meaning saplings accumulate more starch for growth (Figure 4.31 & 4.49). During the rainy season, saplings apparently gain more carbon through photosynthesis process due to sufficient light (Poorter, 2007). There is a significant interaction on all non-structural carbohydrates storage for seedlings. The significant interaction of non-structural carbohydrate compounds and location on seedlings is due to wide discrepancies between Ncumcara fire history treatments combinations and other sites (Figures 4.32– 4.34).

For saplings oligosaccharides and polysaccharides have significant differences between locations and between fire history treatments while starch was only significant between fire history treatments (Figures 4.50 – 4.54). This might be translated that starch is more strongly influenced by fire history while the sugars influenced by several site factors that might include: a) different rainfall, b) different management, c) different fire return interval and fire intensity, d) different level of domestic and game animals, and e) different competition from other plants.

Once more, recently burnt treatments for the saplings have the highest sugars and starch compared to recently unburnt treatments (Figures 4.51, 4.53 – 4.54). However, according to Schultz 2011, saplings usually have low starch reserves at the end of dry season due to browsing and defoliation. Again, repeated fires deplete root carbohydrates that may compromise resprouting. The research findings also revealed the linear positive correlation between taproot mass and taproot diameter for both seedlings and saplings which means taproot mass increases as the taproot diameter increases. Therefore taproot mass has a strong positive correlation with the taproot diameter increment, which is to be expected. This relationship could be used for future studies by measuring taproot diameter without damaging the tree. Furthermore, the relationship between taproot mass and shoot mass for both seedlings and saplings is very weak. This may be due to the occurrence of a big taproot with very small shoots above the ground as a result of fire damage.

It also means that shoot mass is a very poor indicator of the stage of development in young *Pterocarpus. angolensis* trees. However, the effect of taproot mass on shoot mass and height is significant meaning a change in taproot mass causes changes to shoot mass and height (Tables 4.19 – 4.20 & 4.31 – 4.32).

Non-structural carbohydrate storage is vital for tree growth and survival due to stress and disturbances. Therefore, storage of non-structural carbohydrate in the taproot facilitates shoot growth after dry season and inadequate carbohydrates storage causes the tree to take long to recover after disturbances (Poorter & Katajima, 2007). NSC storage contains simple sugars (oligosaccharides and polysaccharides) and starch. Therefore, this study found NSC compounds have strong positive relationships with taproot mass for both seedlings and saplings (Figures 4.36 – 4.38 & 4.56 – 4.58).

The reader is referred to Tables 4.20 – 4.22 & 4.30 – 4.32 where the slope and intercept of the fitted lines depicting the relationship between taproot mass and NSC's are shown. The slope parameters for seedlings ranges from 1.04 – 1.10 and for saplings it ranges from 0.74 – 0.79. The steeper slopes for the saplings indicate that the effect of taproot mass on non-structural carbohydrates is higher for seedlings than saplings. With increasing taproot mass of seedlings the non-structural carbohydrate increases more.

Another finding is that the non-structural carbohydrate storage content is higher in saplings compared to seedlings. This finding confirms that sugars and starch accumulate in taproot with increasing tree age and with increasing size of the taproot. The same trend, but more marked, is discernible with starch accumulation (Figures 4.40 & 4.60). It reveals that starch is the most important compound for carbohydrate storage, but also shows that substantial portions of poly- and oligosaccharides are stored in taproots. It is also clear that the mean taproot mass is much greater than the mean above ground biomass (shoot mass) during the seedling and sapling stages of development.

5.6 Tree age estimates from tree ring analysis

The ages of the tree was estimated by counting the number of growth rings on the neck discs and the results are presented in this section. Based on the study by Kasumu (1998), the suffrutex stage may be prolonged for 12 years or more until the root system is able to use water and nutrients for survival, while Munthali (1999) states that suffrutex stage under natural Miombo woodlands conditions lasts for 8-15 years. Respondents' estimation of suffrutex stage duration varies but the majority (35 %) estimated that seedling takes 5 years to reach sapling stage. On the other hand, 30 % of the respondents indicated that sapling takes 5 to 10 years to reach bole tree stage (Figure 4.4). This study found that the number of growth rings ranges from 5 to 21 per taproot neck disc whereby Caprivi recorded the highest number of rings per neck disc. Furthermore, the average growth rings per location are Okongo 8, Ncumcara 9 and Caprivi 9, while per fire history, recently burnt treatments is 9 and recently unburnt treatments is 8.

This finding per neck disc confirms that suffrutex stage takes on average approximately 8-9 years, but that the range in ages can vary from 5 to 21 years in extreme cases. The mean values is close to Kasumu (1998) and Munthali (1999) findings of 12 years and more, and 8 - 15 years respectively. The relatively wide range in ages of the suffrutex stage might be as a result of geographical and landscape condition discrepancies. The highest number of growth rings of 21 (as the outlier in Figure 4.39) per seedling taproot neck observed at Caprivi in recently burnt treatment might be due to fires and animal browsing that kill seedling shoots every year causing seedlings to have prolonged die-back.

Conversely, there is no significant differences observed between locations and also between fire history treatments on both seedling and sapling growth rings, which means the different rainfall gradient between locations and different burning periods between fire history treatments do not significantly influence growth ring numbers. Again, there is no significant relationship found between growth rings with both seedling and sapling taproot mass and shoot mass and height but a weakly significant relationship was observed between growth rings and taproot diameter. This implies that taproot diameter increases with increasing number of growth rings. However, higher numbers of growth rings are found on most of the samples with greater taproot mass than in low taproot mass.

5.7 Factors affecting *Pterocarpus angolensis* development

There are different factors that contribute to the shortage of *Pterocarpus angolensis* natural recruitment in the forest such as temperature, drought, diseases, animal browsing and human cutting (Graz, 2004; Banda *et al*., 2006). Takawira-Nyenya (2008) states fires and removing of other vegetation as important in the ecology of *Pterocarpus angolensis* by reducing uptake of nutrients in the soil as well as use of sunlight and space by other plants. Full light conditions and removal of root competition contributes to the development of saplings from suffrutices (Mwitwa *et al*., 2008). In addition to the above mentioned factors respondents stated soil fertility, sunlight, plant competition and fires in descending order.

Furthermore, 93 % of the respondents alleged partial removal of competing vegetation while 88 % respondents indicated that absence of fires in one fire season has large effect on the tree development from sapling to bole tree stage. Other factors stated by most of the respondents that have large effects are higher than average rainfall along with absence of game and domestic animals. According to the respondents *Pterocarpus angolensis* grows well and fast in open space whereas domestic animals and game destroy seedlings by browsing. Forest fires destroy seedlings, so the absence of fire for one or two fire seasons will markedly reduce seedling die-back (Sections 4.2.7 to 4.2.13).

A study by Caro *et al.* (2005) also describes full light, absence of fires, absence of root competition and sufficient supply of mineral nutrients promote tree growth from seedlings to sapling stage. As indicated by most of the respondents (95 %) of all the study locations that seedlings are vulnerable to fires while 84 % and 89 % indicated saplings and mature trees respectively resistant to fires (Figure 4.8). Similarly, Mehl *et al.* (2010) describes saplings with a thick corky bark are extremely fire resistant and can survive temperatures of up to 450 °C. It is also assumed that saplings have higher moisture contents than seedlings and they are above the grass level. However, respondents stated saplings are only resistant under low intensity fires. Respondents also mentioned that mature trees with dry bark and patches of partial stem die-back on the lower trunk are vulnerable to fires. It is clear from the interviews and the literature that fires can have positive and negative effects on seedling numbers, apparently depending on the fire intensity. Our data at Okongo was inconclusive, but data from Ncumcara and Caprivi suggest that frequent fires, (probably low-intensity fires that partially remove competition) are more favourable for seedling and sapling frequency than the absence of fire for several years (see smaller height classes in Figure 4.17).

5.8 Tree damage and stand disturbances

During this study some of the trees were observed dead with burnt scars on stems and shoots, damaged taproot sides, rotten stem parts as well as debarked stems and defoliated branches and shoots. Cutting of *Pterocarpus angolensis* trees was also observed. In all recently burnt treatments in the three locations it was observed that many of the trees were damaged by fires (at Okongo 67 % of the trees, Ncumcara 71 % and Caprivi 100 %).

The majority of respondents from Ncumcara (87 %) and Caprivi (100 %) indicated fires as the most common disturbance that affect *Pterocarpus angolensis* development. As stated by most of the respondents seedlings are not resistant to fires. Hence, at Ncumcara and Caprivi where fires occur every year as indicated by the majority of respondents suffrutex stage is likely to take many years. In addition, human cutting was indicated by respondents especially at Ncumcara as the main disturbance to *Pterocarpus angolensis* natural regeneration. Respondents again highlighted temperature, wind, lightning, plant competition, insects, diseases and drought as the other disturbances. Very low temperature (frost) kills seedlings, wind and lightning cause damage to saplings and branches. Competition with other plants restrict nutrients supply to the tree while drought causes tree stress and makes it susceptible to disease and insect attacks.

Chapter 6: Conclusions and recommendations

6.1 Introduction

This chapter concludes the findings obtained from this study as well as the recommendations. The findings are from the three study locations (Okongo, Ncumcara and Caprivi) with different rainfall gradient whereby two fire history treatments of different fire intervals allocated to each study location.

6.2 Conclusions

Several literature papers present *Pterocarpus angolensis* (Kiaat tree) as a vital tree species for the livelihood of people by providing good quality timber, wood carvings and other non-timber products such as medicines. Currently, this tree species is mainly germinating and developing naturally in forest and being exploited indiscriminately. The Kiaat tree grows in dry forest with low rainfall and low nutrient levels, but fortunately it is resistant to fires and fixes atmospheric nitrogen. The tree seedlings undergo a prolonged suffrutex stage before reaching sapling stage due to yearly shoot die-back.

This study found the regeneration of Kiaat tree very poor because seedlings density (10%) is lowest in all three locations in comparison with saplings (33%) and mature trees (56%). In addition, seedling differences between study locations and fire history treatments were found non-significant meaning seedling abundance is similar across study locations and fire history treatments. Saplings and mature trees abundance was discovered statistically significant whereby Ncumcara recorded the highest saplings while Okongo noted the highest mature trees.

In a different note most of the respondents of Ncumcara and Caprivi suggested saplings is abundant followed by seedlings then mature trees, but Okongo respondents rated mature trees as being most abundant, followed by saplings and then seedlings. Additionally, a high number of respondents rated seedlings as sparse followed by saplings then mature trees.

Statistical analysis indicated that BA of saplings was not significantly different between study locations but only significant between fire history treatments whereby a high BA was observed at recently unburnt treatments. This is confirmed in Schutz (2011) that repeated fires deplete carbohydrates reducing sapling diameter. Okongo has the highest tree sapling DBH compared to other two study locations. The mean DBH difference between locations is significant but not significant between fire history treatments. This difference is observed between Okongo and Ncumcara and Caprivi but not between Ncumcara and Caprivi as their noticeable mature tree difference is not so prominent. For bole tree the combination of study locations with fire history treatments has a strong effect on the tree DBH.

Pterocarpus angolensis is regarded as fire resistant species and its growth in the adult stage is not negatively affected by fires (Vermeulen, 1990). Interestingly, respondents highlighted that fires destroy most of the seedlings and some saplings when fire intensity is high. The mature tree is presented as more resistant to fires and it can only be destroyed by fires if its bark is extremely dry and if it has dry stem patches. Hence, every year fire occurrences and high intensity fires reduce the number of seedlings to reach sapling stages then as a result prolong the suffrutex stage. The study discovered that fire is the main tree disturbance but it also positively influences the development of *Pterocarpus angolensis* by breaking seed coat and removing other vegetation to reduce competition in the three study locations (Figures 4.5: A, B & C). There is no fire management and silvicultural practices being performed that can reduce fire impact and enhance *Pterocarpus angolensis* growth.

Soil analysis results confirm soil texture is generally sandy and acidic with low levels of organic carbon, phosphorus and exchangeable base cations. A study by Stahle *et al*. (1999), Miombo woodland soils which is found in the three study locations is acidic with little extractable phosphorus, low cation exchange capacities with low nitrogen levels and whereby soil organic matter only high under densely wooded plants.

The higher pH, phosphorus and organic carbon in Caprivi recently burnt treatments are a result of recent fires that make them available to trees. Many respondents suggested soil nutrients (fertility) plays a vital role on *Pterocarpus angolensis* growth.

So low levels of organic carbon, pH and phosphorus may affect the tree growth in Okongo and Ncumcara where tree stocking observed was low. Low organic carbon means nitrogen availability is also low due to slow mineralisation processes as a result of drought experienced in the three forests. Nevertheless, *Pterocarpus angolensis* is capable of fixing atmospheric nitrogen. Even though the soil is not fertile phosphorus availability is adequate because normally the demand of phosphorus by tree is low. Low level of ECEC is due to lack of charges on the soil particle surfaces which is common in sandy soils. The sum of exchangeable base cations is less than 5 $cmol_c$ kg^{-1} meaning the soil is dystrophic and thus has low fertility.

The findings show that in all study locations and fire history treatments, mean below-ground biomass (taproot mass) is higher than mean above-ground biomass (shoot mass). Taproot mass do not have a relationship with taproot depth, so taproot mass does not necessarily influence taproot depth to reach moisture reserves.

Pterocarpus angolensis taproot non-structural carbohydrates storages consist of simple sugars, oligosaccharides, polysaccharides and starch that facilitate seedling maintenance during the suffrutex stage. For saplings a slightly higher content of oligosaccharides is found in a lower rainfall (500 mm) of Okongo while polysaccharides found in the middle rainfall (600 mm) Ncumcara. All the non-structural carbohydrates are highest in the recently burnt treatments. There is a strong positive relationship between sugars and starch with taproot mass but not with shoot mass.

The age of the seedlings and saplings can be determined by counting growth rings on the neck disc of the taproot. The vessels and parenchyma cells are distinct to be used as boundaries between growth rings. The suffrutex stage in the three study locations ranges from 5 to 21 years and at average is 9 years for both seedlings and saplings. In general all the variables analysed do not have significant influence on the shoot growth.

There is no significant difference on ages of the *Pterocarpus angolensis* suffrutex stage between study locations and between fire history treatments. Rainfall gradient and fire intervals do not significantly influence tree ages. The results found non-structural carbohydrate storage does not have any effect on the growth rings as statistical analysis observed non-significant differences. The most important contribution to the body of evidence discovered by this study is the contents of sugars and starch in the taproot that enable seedlings and saplings to resprout after fires and drought. A combination of social survey and ecological survey to investigate ecological process provided a more detailed understanding of the ecological process than each approach on its own.

6.3 Recommendations

i. This study reveals *Pterocarpus angolensis* natural regeneration needs some intervention to promote its development. The intervention should be focused on the fire management and implementations of silvicultural practices. Low fire intensity prescribed burning at the onset of dry season can be carried out on a two year interval to promote seeds germination and provide adequate time for seedling growth. There is a great potential for *Pterocarpus angolensis* natural regeneration provided there is intervention mainly at community level.

ii. Plots with suffrutices of *Pterocarpus angolensis* in the forest should be identified, demarcated and protected from fires for the first years as well as from animals and humans till seedlings reach sapling stage. This can reduce suffrutices death by fires as seedlings are not resistant to fires. Additionally, any attempt to raise tree seedlings should create environmental conditions similar to the favourable natural environment of *Pterocarpus angolensis* in the forest.

iii. The findings of this study were obtained from small sample size that might be too small within the population size and can lead to sampling error. So, a larger size sample should be appropriate to further find out the natural regeneration of the *Pterocarpus angolensis* in the same locations.

iv. Random sample techniques is difficult to be performed to this type of study as the *Pterocarpus angolensis* tree does not cover the whole forest and burnt plots can only be identified in the field. Again, this study was conducted during fire season and some of the identified fire history treatment plots were burnt before field work. Therefore, the selection of the season which is appropriate for the field work should be considered.

v. Based on this study non-structural carbohydrate storage consists of sugars (oligosaccharides and polysaccharides) and starch, further study is required to determine how these sugars and starch facilitate the suffrutices to withstand drought and fires for several years without a permanent shoot.

vi. The ages of *Pterocarpus angolensis* suffrutices can be estimated by counting the growth rings of the neck disc, but future estimation of suffrutices ages, cores from neck disc could be used to avoid the destruction of seedlings.

vii. *Pterocarpus angolensis* development can be improved by carrying out a study on genetically superior selection to find out if the period of suffrutex stage can be reduced and to produce healthy trees.

viii. The parameters such as shoot height and mass, taproot mass, depth and diameter as well as abundance of seedlings, saplings and mature trees, soil properties, fires occurrences and annual average rainfall can be used to develop a model to predict natural regeneration potential of *Pterocarpus angolenssis* in the forest. Non-structural carbohydrates storage content is also a vital variable that can be included because it maintains the suffrutices during drought and then facilitate re-sprouting afterwards.

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Appendices

Appendix 1: Survey questionnaire

Date:

Dd		mm		yy	

Study Region ________________________________

SECTION 1: DETAILS OF INTERVIEWEE

1. Village:...

2. Gender of interviewee

Male		Female	

3. Age of interviewee

<30		30 - 50		50+	

4. Occupation / Livelihood (activity that brings you in contact with the forest).

SECTION 2: Questions on *Pterocarpus* regeneration

1. Do you have *Pterocarpus angolensis* seedlings, saplings and/or mature trees in your area?

   No

   ☐

   Yes

   ☐

   If yes rate them

   a) Seedlings

Less		Average		More	

b) Saplings

Less		Average		More	

c) Pole / mature trees

Less		Average		More	

2. What are the different stages of *Pterocarpus angolensis* development?
3. Do you know how *Pterocarpus angolensis* germinates in the forest?

   Yes or No

   If yes state how is it germinate

4. How many years does *Pterocarpus angolensis* seedling take to reach the sapling stage?
5. Do you know how *Pterocarpus angolensis* advances from the seedling stage to the bole stage in the forest?

   Yes or No

   If yes explain

6. Please estimate the number of years that it takes to advance from sapling to bole stage (alternatively, please give a range of years if you think it is a better reflection of reality,

   a).0 - 5 years ☐

   b).5 - 10 years ☐

   c) 10 - 15 years) ☐

   d) 15- 20 years) ☐

   e) > 20 years) ☐

7. What are the edaphic and environmental factors influencing *Pterocarpus angolensis* development from saplings to bole tree stage ?

8. Management operations that affect *Pterocarpus angolensis* development from sapling to bole tree stage (Try to score it using 4 categories, e.g. the operation has no effect, small effect, medium effect or large effect).

    a. Absence of fire during one fire season

No effect		Small effect		Medium effect		Large effect	

    b. Absence (or low levels of) of domestic livestock

No effect		Small effect		Medium effect		Large effect	

    c. Absence (or low levels of) game animals that browse the trees

No effect		Small effect		Medium effect		Large effect	

    d. Partial removal of competing vegetation in the neighbourhood of the tree (e.g. by harvesting or utilizing neighbouring trees or grasses).

No effect		Small effect		Medium effect		Large effect	

    e. Higher than average rainfall in a particular year

No effect		Small effect		Medium effect		Large effect	

    f. Any other factor not listed above (and give its effect)

No effect		Small effect		Medium effect		Large effect	

9. What are the environmental disturbances that affect *Pterocarpus angolensis* development from saplings to bole stage?
10. How often does the fire occur in your area?
11. Mention *Pterocarpus angolensis* development stages that are resistant to fire and those not resistant to fire

    a) Fire resistant

b) Not fire resistant

12. Does the community perform some silvicultural practices to promote *Pterocarpus angolensis* growth?

    Yes / No

    If yes explain

13. Mention methods (Silvicultural practices) being used to enhance *Pterocarpus angolensis* development from saplings to bole stage crops ?

Thank you

Appendix 2: Vegetation sampling form; Inventory

Vegetation sampling form: Inventory

Region.. **Date**..

Study location.. **Enumerator**......................................

Study site (1 = 1-2 years since fires, 2 = ≥ 4 years since fires): ....

Sampling plot (1,2,3,4)...

Coordinate...

Annual Aver. rainfall..

Annual Aver. Temp. (degrees): Max.... Min .... **Classes (m)**

0-0.5 = 1, 0.5-1 = 2, 1-1.5 = 3, 1.5-2 = 4, 2-2.5 = 5, 2.5-3 = 6

Seedling (Suffrutice) = 0 - 1, Sapling = 1 - 3, Mature tree / pole (bole) stage = >3,

Tree no.		DBH (cm)	Height (m)	No. of shoot	Condition	Seedling/Sapling/Mature (Sdg/S/M)	Class (1-6) / >3	Disturbance type (eg browsing)		Damage				
										High	Medium	Low	Evidence (eg defoliation)	

Appendix 3: Vegetation destructive sampling; Taproots

Vegetation destructive sampling: Taproot

Region: .... **Date:** ....

Study location: .... **Enumerator:** ....

Study site (1 = 1-2 years since fires, 2 = ≥ 4 years since fires): ....

Sampling plot (1,2,3,4)...

Coordinate..

Annual Aver. rainfall..

Annual Aver. Temp. (degrees): Max .... **Min** .... **Classes (m)**

0-0.5 = 1, 0.5-1 = 2, 1-1.5 = 3, 1.5-2 = 4, 2-2.5 = 5, 2.5-3 = 6

Sapling no.	Tuber diameter (cm)	Shoot diameter (cm)	Shoot height (m)	Root depth (m) up to 1 m	No. of shoots	Condition	Neck diameter (cm)	Neck mass (kg)	Shoot Mass (kg)	Root Mass (kg)	Core mass (kg)			Core height (m)	Shoot section (kg)	Lateral roots	Old shoots evidence	Class (1-6) / >3	Comments eg. Coppicing
											Top	Bottom	Top	Bottom					

Appendix 4: Soil sampling form

Soil sampling form		
Region..	**Date:**.....................	
Study location..		
Study site (1 = 1-2 years since fires, 2 = ≥ 4 years since fires):..		
Sampling plot (1,2,3,4)...		
Coordinate...		
Annual Aver. rainfall…...		
Annual Aver. Temp. (degrees): Max .... **Min**		
Horizon (A or B)……………………………………………………………………………		
Oven dry:............		
Dry Mass:…… **…………………………………...**		
Wet Mass:…………………………………………..		

Appendix 5: Okongo soil analysis

Boord	Lab. No.	Diepte (cm)	Grond	pH (KCl)	Weerst. (Ohm)	H^+ (cmol/kg)	Klip (Vol %)	P Bray II mg/kg	K	Uitruilbare katione (cmol(+)/kg) Na	K	Ca	Mg	Cu mg/kg	Zn	Mn	B	Fe mg/kg	C %
Site 1- Pl. 1- HA	1724		Sand	4.4		0.55	1	6	16	0.03	0.04	0.35	0.16	0.20	0.1	21.4	0.19	17.52	0.22
Site 1- Pl. 1- HB	1725		Sand	4.2		0.50	1	9	9	0.04	0.02	0.33	0.11	0.18	0.1	4.5	0.11	20.40	0.12
Site 1- Pl. 2- HA	1726		Sand	5.6		0.25	1	5	107	0.03	0.27	1.04	0.33	0.26	0.1	34.0	0.05	15.82	0.17
Site 1- Pl. 2- HB	1727		Sand	4.5		0.45	1	8	14	0.02	0.03	0.49	0.26	0.16	0.2	14.8	0.10	12.61	0.10
Site 1- Pl. 3- HA	1728		Sand	5.0		0.45	1	8	26	0.03	0.07	1.15	0.39	0.32	0.2	33.9	0.22	17.21	0.26
Site 1- Pl. 3- HB	1729		Sand	4.6		0.40	1	11	15	0.03	0.04	0.73	0.47	0.25	0.2	33.1	0.24	17.44	0.15
Site 1- Pl. 4- HA	1730		Sand	4.5		0.60	1	15	19	0.02	0.05	0.71	0.29	0.27	0.2	27.5	0.22	28.68	0.20
Site 1- Pl. 4- HB	1731		Sand	4.1		0.50	1	16	8	0.03	0.02	0.25	0.13	0.26	0.2	5.7	0.34	23.25	0.10
Site 2- Pl. 1- HA	1732		Sand	4.1		0.85	1	10	15	0.02	0.04	0.60	0.25	0.24	0.1	19.8	0.32	28.36	0.35
Site 2- Pl. 1- HB	1733		Sand	4.2		0.45	1	11	6	0.02	0.02	0.17	0.09	0.17	0.1	3.0	0.20	18.83	0.15
Site 2- Pl. 2- HA	1734		Sand	4.3		0.50	1	7	12	0.03	0.03	0.45	0.19	0.25	0.1	15.9	0.21	21.35	0.24
Site 2- Pl. 2- HB	1735		Sand	4.2		0.40	1	11	8	0.02	0.02	0.21	0.08	0.18	0.1	5.0	0.23	23.37	0.12
Site 2- Pl. 3- HA	1736		Sand	4.1		0.50	1	8	22	0.02	0.06	0.45	0.17	0.30	0.2	17.5	0.18	22.19	0.17
Site 2- Pl. 3- HB	1737		Sand	4.4		0.60	1	10	14	0.02	0.04	0.20	0.11	0.24	0.2	4.8	0.29	25.73	0.15
Site 2- Pl. 4- HA	1738		Sand	4.3		0.50	1	13	16	0.02	0.04	0.36	0.18	0.25	0.2	14.7	0.17	24.20	0.12
Site 2- Pl. 4- HB	1739		Sand	4.1		0.50	1	11	10	0.03	0.02	1.25	0.20	0.25	0.2	3.4	0.27	21.39	0.59
Metodes[#]				3108	3106	3109		3117		3113	3113	3113	3113	3115	3115	3115	3114		3107

Boord	Lab. No.	Vog %
Site 1- Pl. 1- HA	1724	0.10
Site 1- Pl. 1- HB	1725	0.10
Site 1- Pl. 2- HA	1726	0.10
Site 1- Pl. 2- HB	1727	0.10
Site 1- Pl. 3- HA	1728	0.10
Site 1- Pl. 3- HB	1729	0.20
Site 1- Pl. 4- HA	1730	0.10
Site 1- Pl. 4- HB	1731	0.00
EAR lab#	Sample numbers:1732	Sample numbers:0 .20
Site 2- Pl. 1- HB	1733	0.00
Site 2- Pl. 2- HA	1734	0.10
Site 2- Pl. 2- HB	1735	0.10
Site 2- Pl. 3- HA	1736	0.10
Site 2- Pl. 3- HB	1737	0.10
Site 2- Pl. 4- HA	1738	0.10
Site 2- Pl. 4- HB	1739	0.10

Boord No.	Lab. No.	Na %	K %	Ca %	Mg %	T-Waarde cmol/kg
Site 1- Pl. 1- HA	1724	2.39	3.72	31.31	13.83	1.13
Site 1- Pl. 1- HB	1725	3.52	2.22	32.96	11.45	1.00
Site 1- Pl. 2- HA	1726	1.48	14.26	54.28	16.96	1.92
Site 1- Pl. 2- HB	1727	1.96	2.75	38.70	20.81	1.26
Site 1- Pl. 3- HA	1728	1.37	3.13	55.17	18.84	2.09
Site 1- Pl. 3- HB	1729	1.95	2.22	43.62	28.27	1.67
Site 1- Pl. 4- HA	1730	1.45	2.87	42.59	17.29	1.68
Site 1- Pl. 4- HB	1731	3.42	2.28	27.04	14.25	0.94
Site 2- Pl. 1- HA	1732	1.20	2.11	34.26	14.23	1.76
Site 2- Pl. 1- HB	1733	2.87	2.13	22.61	11.61	0.74
Site 2- Pl. 2- HA	1734	2.11	2.63	37.57	16.09	1.20
Site 2- Pl. 2- HB	1735	3.35	2.65	28.64	11.44	0.74
Site 2- Pl. 3- HA	1736	2.08	4.67	37.71	13.83	1.20
Site 2- Pl. 3- HB	1737	2.36	3.68	20.69	11.03	0.96
Site 2- Pl. 4- HA	1738	2.25	3.75	32.88	15.95	1.11
Site 2- Pl. 4- HB	1739	1.48	1.23	62.42	9.85	2.00

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Boord	Lab.	Klei	Slik	Fyn Sand	Medium Sand	Growwe Sand	Klip	Klassifikasie	Waterhouvermoë		
No.	No.	%	%	%	%	%	% (v/v)		10 kPa %	100 kPa %	mm/m
Site 1- Pl. 1- HA	1724	6.2	0	40	44.8	9	0.0	Sa	14.10	6.08	80.2
Site 1- Pl. 1- HB	1725	6.2	0	42.8	42	9	0.0	Sa	15.05	6.42	86.3
Site 1- Pl. 2- HA	1726	6.2	0	47.4	39.2	7.22	0.0	Sa	16.16	6.68	94.7
Site 1- Pl. 2- HB	1727	6.2	0	45.2	39.6	9	0.0	Sa	15.87	6.72	91.5
Site 1- Pl. 3- HA	1728	6.2	0	40.1	44.6	9.1	0.0	Sa	14.15	6.11	80.5
Site 1- Pl. 3- HB	1729	8.2	0	41.6	40.8	9.4	0.0	Sa	15.68	7.12	85.6
Site 1- Pl. 4- HA	1730	6.2	0	41.8	44.4	7.64	0.0	Sa	14.34	6.06	82.8
Boord	Lab.	Klei	Slik	Fyn Sand	Medium Sand	Growwe Sand	Klip	Klassifikasie	Waterhouvermoë		
No.	No.	%	%	%	%	%	% (v/v)		10 kPa %	100 kPa %	mm/m
Site 1- Pl. 4- HB	1731	6.2	0	42	43.6	8.2	0.0	Sa	14.57	6.19	83.8
Site 2- Pl. 1- HA	1732	6.2	0	40.2	45.2	8.4	0.0	Sa	14.01	6.00	80.1
Site 2- Pl. 1- HB	1733	6.2	1	42.6	43	7.2	0.0	Sa	15.14	6.54	86.0
Site 2- Pl. 2- HA	1734	6.2	0	36.4	48	9.4	0.0	Sa	12.97	5.70	72.6
Site 2- Pl. 2- HB	1735	6.2	0	41.4	44	8.4	0.0	Sa	14.42	6.15	82.7
Site 2- Pl. 3- HA	1736	6.2	0	43.1	45	5.7	0.0	Sa	14.31	5.90	84.1
Site 2- Pl. 3- HB	1737	6.2	0	43.6	45.2	5	0.0	Sa	14.31	5.85	84.6
Site 2- Pl. 4- HA	1738	4.2	2	43.6	44.2	6	0.0	Sa	14.86	6.14	87.2
Site 2- Pl. 4- HB	1739	6.2	0	49.2	38.6	6	0.0	Sa	16.47	6.70	97.7

Appendix 6: Ncumcara soil analysis

Boord	Lab.	Diepte	Grond	pH	Weerst.	H^+	Klip	P Bray II	K	Uitruilbare katione (cmol(+)/kg)				Cu	Zn	Mn	B	Fe	C
	No.	(cm)		(KCl)	(Ohm)	(cmol/kg)	(Vol %)	mg/kg		Na	K	Ca	Mg	mg/kg				mg/kg	%
28- Site 1- P. 1- HA	1708		Sand	4.4		0.55	1	8	9	0.02	0.02	0.82	0.17	0.18	0.1	9.4	0.16	38.46	0.25
28- Site 1- P. 1- HB	1709		Sand	4.2		0.35	1	10	6	0.02	0.02	0.24	0.05	0.17	0.1	1.2	0.21	35.59	0.10
28- Site 1- P. 2- HA	1710		Sand	4.7		0.45	1	9	10	0.03	0.03	0.75	0.21	0.20	0.1	24.3	0.22	12.41	0.27
28- Site 1- P. 2- HB	1711		Sand	4.2		0.25	1	10	5	0.02	0.01	0.15	0.05	0.18	0.1	1.3	0.02	13.64	0.16
28- Site 1- P. 3- HA	1712		Sand	4.7		0.40	1	7	8	0.03	0.02	0.57	0.15	0.18	0.1	13.9	0.25	12.25	0.22
28- Site 1- P. 3- HB	1713		Sand	4.4		0.30	1	7	4	0.02	0.01	0.14	0.04	0.16	0.1	1.0	0.10	12.57	0.17
28- Site 1- P. 4- HA	1714		Sand	4.4		0.60	1	13	11	0.04	0.03	0.72	0.19	0.18	0.3	15.9	0.26	18.28	0.23
28- Site 1- P. 4- HB	1715		Sand	4.2		0.30	1	11	5	0.02	0.01	0.16	0.04	0.19	0.1	0.8	0.27	19.29	0.12
28- Site 2- P. 1- HA	1716		Sand	4.7		0.55	1	12	20	0.02	0.05	0.93	0.23	0.32	0.3	31.8	0.15	31.70	0.25
28- Site 2- P. 1- HB	1717		Sand	4.5		0.35	1	11	9	0.02	0.02	0.38	0.12	0.21	0.2	5.4	0.30	19.50	0.12
28- Site 2- P. 2- HA	1718		Sand	4.8		0.55	1	6	15	0.02	0.04	1.12	0.21	0.36	0.3	33.8	0.19	25.95	0.18
28- Site 2- P. 2- HB	1719		Sand	4.9		0.30	1	4	6	0.02	0.02	0.32	0.08	0.20	0.1	3.4	0.34	13.30	0.10
28- Site 2- P. 3- HA	1720		Sand	4.9		0.45	1	8	12	0.03	0.03	0.89	0.18	0.26	0.2	23.1	0.32	18.56	0.14
28- Site 2- P. 3 HB	1721		Sand	4.6		0.30	1	12	7	0.03	0.02	0.30	0.10	0.20	0.2	2.5	0.32	15.34	0.15
28- Site 2- P. 4 HA	1722		Sand	4.4		0.70	1	9	14	0.03	0.04	0.99	0.17	0.24	0.2	21.8	0.06	28.65	0.19
28- Site 2- P. 4 HB	1723		Sand	4.3		0.40	1	15	9	0.03	0.02	0.48	0.10	0.15	0.1	6.0	0.25	23.71	0.15
Metodes[#]				3108	3106	3109		3117		3113	3113	3113	3113	3115	3115	3115	3114		3107

Boord	Lab. No.	Vog %
28- Site 1- P. 1- HA	1708	0.10
28- Site 1- P. 1- HB	1709	0.10
28- Site 1- P. 2- HA	1710	0.10
28- Site 1- P. 2- HB	1711	0.00
28- Site 1- P. 3- HA	1712	0.10
28- Site 1- P. 3- HB	1713	0.10
28- Site 1- P. 4- HA	1714	0.10
28- Site 1- P. 4- HB	1715	0.00
28- Site 2- P. 1- HA	1716	0.10
28- Site 2- P. 1- HB	1717	0.10
28- Site 2- P. 2- HA	1718	0.10
28- Site 2- P. 2- HB	1719	0.00
28- Site 2- P. 3- HA	1720	0.10
28- Site 2- P. 3 HB	1721	0.00
28- Site 2- P. 4 HA	1722	0.10
28- Site 2- P. 4 HB	1723	0.00
Metodes[#]		

Boord No.	Lab. No.	Na %	K %	Ca %	Mg %	T-Waarde cmol/kg
28- Site 1- P. 1- HA	1708	1.30	1.52	51.56	10.90	1.58
28- Site 1- P. 1- HB	1709	3.21	2.24	35.20	7.58	0.68
28- Site 1- P. 2- HA	1710	1.74	1.78	51.56	14.11	1.46
28- Site 1- P. 2- HB	1711	5.08	2.50	30.45	9.72	0.48
28- Site 1- P. 3- HA	1712	2.18	1.75	49.15	12.67	1.17
28- Site 1- P. 3- HB	1713	4.53	1.94	27.08	7.33	0.51
28- Site 1- P. 4- HA	1714	2.44	1.72	45.73	11.86	1.57
28- Site 1- P. 4- HB	1715	4.58	2.25	29.72	8.05	0.54

Boord No.	Lab. No.	Na %	K %	Ca %	Mg %	T-Waarde cmol/kg
28- Site 2- P. 1- HA	1716	1.30	2.87	52.11	13.06	1.79
28- Site 2- P. 1- HB	1717	2.69	2.60	42.49	13.42	0.90
28- Site 2- P. 2- HA	1718	1.25	1.98	57.66	10.88	1.95
28- Site 2- P. 2- HB	1719	3.03	2.17	43.91	10.31	0.74
28- Site 2- P. 3- HA	1720	1.61	2.01	56.49	11.23	1.57
28- Site 2- P. 3 HB	1721	3.90	2.43	40.37	12.95	0.74
28- Site 2- P. 4 HA	1722	1.42	1.87	51.54	8.76	1.92
28- Site 2- P. 4 HB	1723	2.71	2.27	46.58	9.83	1.04

Meganiese ontleding

Boord	Lab.	Klei	Slik	Fyn Sand	Medium Sand	Growwe Sand	Klip	Klassifikasie	Waterhouvermoë		
No.	No.	%	%	%	%	%	% (v/v)		10 kPa %	100 kPa %	mm/m
28- Site 1- P. 1- HA	1708	4.2	0	33.8	57.2	4.8	0.0	Sa	9.97	3.83	61.4
28- Site 1- P. 1- HB	1709	4.2	0	49.6	43.4	2.8	0.0	Sa	14.85	5.43	94.2
28- Site 1- P. 2- HA	1710	4.2	0	27.7	65	3.1	0.0	Sa	7.46	2.79	46.6
28- Site 1- P. 2- HB	1711	4.2	0	43	51.24	1.62	0.0	Sa	12.27	4.40	78.7
28- Site 1- P. 3- HA	1712	4.2	0	25.6	67	3.2	0.0	Sa	6.77	2.55	42.1
28- Site 1- P. 3- HB	1713	4.2	2	51	40.6	2.2	0.0	Sa	16.42	6.40	100.1
28- Site 1- P. 4- HA	1714	4.2	2	39.8	51.6	2.4	0.0	Sa	12.65	5.06	75.9
28- Site 1- P. 4- HB	1715	4.2	2	52.4	39.4	2	0.0	Sa	16.84	6.54	103.0
28- Site 2- P. 1- HA	1716	4.2	0	48.6	45	2.2	0.0	Sa	14.36	5.21	91.5
28- Site 2- P. 1- HB	1717	4.2	2	53.4	38.4	2	0.0	Sa	17.18	6.66	105.2
28- Site 2- P. 2- HA	1718	6.2	3	37.8	50	3	0.0	Sa	13.68	6.15	75.3
28- Site 2- P. 2- HB	1719	4.2	2	49.4	42	2.4	0.0	Sa	15.92	6.24	96.8
28- Site 2- P. 3- HA	1720	4.2	0	40.2	52.2	3.4	0.0	Sa	11.80	4.38	74.2
28- Site 2- P. 3 HB	1721	4.2	0	42.6	49.6	3.6	0.0	Sa	12.67	4.71	79.6
28- Site 2- P. 4 HA	1722	4.2	0	40.6	52.4	2.8	0.0	Sa	11.78	4.33	74.5
28- Site 2- P. 4 HB	1723	6.2	2	47	42.2	2.6	0.0	Sa	16.09	6.76	93.4

Appendix 7: Caprivi soil analysis

Boord	Lab. No.	Diepte (cm)	Grond	pH (KCl)	Weerst. (Ohm)	H^+ (cmol/kg)	Klip (Vol %)	P Bray II mg/kg	K	Uitruilbare katione (cmol(+)/kg) Na	K	Ca	Mg	Cu mg/kg	Zn	Mn	B	Fe mg/kg	C %
27- Site 1- P. 1- HA	1692		Sand	5.8		0.45	1	16	60	0.03	0.15	1.35	0.37	0.38	0.5	32.6	0.50	26.01	0.30
27- Site 1- P. 1- HB	1693		Sand	4.6		0.50	1	11	28	0.02	0.07	0.48	0.15	0.28	0.2	9.7	0.48	28.67	0.12
27- Site 1- P. 2- HA	1694		Sand	5.5		0.30	1	11	31	0.03	0.08	1.72	0.59	0.42	0.5	46.3	0.11	21.38	0.63
27- Site 1- P. 2- HB	1695		Sand	4.3		0.50	1	10	13	0.02	0.03	0.31	0.18	0.24	0.2	4.1	0.30	23.72	0.21
27- Site 1- P. 3- HA	1696		Sand	5.0		0.35	1	13	17	0.03	0.04	0.85	0.34	0.32	0.2	13.0	0.32	14.67	0.29
27- Site 1- P. 3- HB	1697		Sand	4.2		0.50	1	8	9	0.03	0.02	0.28	0.10	0.21	0.1	2.2	0.30	17.44	0.17
27- Site 1- P. 4- HA	1698		Sand	5.1		0.40	1	8	21	0.02	0.05	0.96	0.39	0.28	0.1	14.5	0.29	13.48	0.34
27- Site 1- P. 4- HB	1699		Sand	4.2		0.45	1	14	8	0.03	0.02	0.18	0.10	0.20	0.1	1.6	0.33	18.46	0.17
27- Site 2- P. 1- HA	1700		Sand	4.4		0.50	1	14	27	0.03	0.07	0.57	0.14	0.24	0.1	16.6	0.21	20.39	0.34
27- Site 2- P. 1- HB	1701		Sand	4.1		0.50	1	8	15	0.03	0.04	0.22	0.08	0.22	0.1	1.8	0.22	23.90	0.10
27- Site 2- P. 2- HA	1702		Sand	4.4		0.45	1	7	18	0.02	0.05	0.52	0.19	0.22	0.2	10.2	0.27	16.43	0.22
27- Site 2- P. 2- HB	1703		Sand	4.1		0.45	1	5	14	0.02	0.04	0.27	0.10	0.20	0.2	1.0	0.34	17.22	0.15
27- Site 2- P. 3- HA	1704		Sand	4.9		0.45	1	7	17	0.03	0.04	1.07	0.18	0.22	0.2	25.7	0.25	23.15	0.32
27- Site 2- P. 3- HB	1705		Sand	4.3		0.40	1	9	9	0.02	0.02	0.28	0.06	0.15	0.1	2.1	0.14	28.65	0.25
27- Site 2- P. 4- HA	1706		Sand	4.5		0.70	1	6	15	0.03	0.04	0.92	0.21	0.29	0.2	37.4	0.28	27.97	0.18
27- Site 2- P. 4- HB	1707		Sand	4.2		0.35	1	9	9	0.03	0.02	0.19	0.06	0.17	0.1	2.3	0.08	27.24	0.19
Metodes[#]				3108	3106	3109		3117		3113	3113	3113	3113	3115	3115	3115	3114		3107

Boord	Lab. No.	Vog %
27- Site 1- P. 1- HA	1692	0.20
27- Site 1- P. 1- HB	1693	0.10
27- Site 1- P. 2- HA	1694	0.30
27- Site 1- P. 2- HB	1695	0.10
27- Site 1- P. 3- HA	1696	0.20
27- Site 1- P. 3- HB	1697	0.20
27- Site 1- P. 4- HA	1698	0.20
27- Site 1- P. 4- HB	1699	0.10
27- Site 2- P. 1- HA	1700	0.10
27- Site 2- P. 1- HB	1701	0.10
27- Site 2- P. 2- HA	1702	0.10
27- Site 2- P. 2- HB	1703	0.10
27- Site 2- P. 3- HA	1704	0.10
27- Site 2- P. 3- HB	1705	0.10
27- Site 2- P. 4- HA	1706	0.20
27- Site 2- P. 4- HB	1707	0.10
Metodes#		

Boord No.	Lab. No.	Na %	K %	Ca %	Mg %	T-Waarde cmol/kg
27- Site 1- P. 1- HA	1692	1.36	6.56	57.35	15.57	2.35
27- Site 1- P. 1- HB	1693	1.76	5.81	39.30	11.96	1.21
27- Site 1- P. 2- HA	1694	0.93	2.95	63.22	21.86	2.72
27- Site 1- P. 2- HB	1695	2.35	3.18	29.83	16.98	1.05
27- Site 1- P. 3- HA	1696	1.71	2.65	52.92	20.97	1.61
27- Site 1- P. 3- HB	1697	3.01	2.45	29.81	10.68	0.92
27- Site 1- P. 4- HA	1698	1.32	2.98	52.59	21.29	1.83
27- Site 1- P. 4- HB	1699	3.77	2.69	23.00	12.44	0.77
27- Site 2- P. 1- HA	1700	2.17	5.33	43.39	10.73	1.30
27- Site 2- P. 1- HB	1701	2.96	4.43	25.48	8.85	0.86
27- Site 2- P. 2- HA	1702	2.03	3.76	42.08	15.42	1.23
27- Site 2- P. 2- HB	1703	2.79	4.15	30.77	11.35	0.88
Boord No.	Lab. No.	Na %	K %	Ca %	Mg %	T-Waarde cmol/kg
27- Site 2- P. 3- HA	1704	1.48	2.46	60.51	10.18	1.77
27- Site 2- P. 3- HB	1705	3.06	2.75	35.38	8.21	0.79
27- Site 2- P. 4- HA	1706	1.32	2.08	48.47	11.17	1.89
27- Site 2- P. 4- HB	1707	4.48	3.55	29.15	9.15	0.65

Meganiese ontleding

Boord	Lab.	Klei	Slik	Fyn Sand	Medium Sand	Growwe Sand	Klip	Klassifikasie	Waterhouvermoë		
No.	No.	%	%	%	%	%	% (v/v)		10 kPa %	100 kPa %	mm/m
27- Site 1- P. 1- HA	1692	4.2	0	49.2	40	6.6	0.0	Sa	15.68	6.03	96.6
27- Site 1- P. 1- HB	1693	4.2	0	51.8	38.6	5.44	0.0	Sa	16.25	6.13	101.2
27- Site 1- P. 2- HA	1694	4.2	0	43	47.6	5.2	0.0	Sa	13.21	5.03	81.8
27- Site 1- P. 2- HB	1695	4.2	0	53.7	38	4.1	0.0	Sa	16.58	6.16	104.3
27- Site 1- P. 3- HA	1696	4.2	0	44.8	44.6	6.42	0.0	Sa	14.12	5.45	86.8
27- Site 1- P. 3- HB	1697	4.2	0	50.3	39.5	6	0.0	Sa	15.90	6.06	98.5
27- Site 1- P. 4- HA	1698	4.2	0	48	43.24	4.64	0.0	Sa	14.73	5.52	92.1
27- Site 1- P. 4- HB	1699	4.2	0	51.4	39.6	4.8	0.0	Sa	15.97	5.99	99.8
27- Site 2- P. 1- HA	1700	4.2	0	44	44.8	7	0.0	Sa	14.01	5.45	85.6
27- Site 2- P. 1- HB	1701	4.2	0	43	44.8	8	0.0	Sa	13.92	5.50	84.2
27- Site 2- P. 2- HA	1702	4.2	0	41.8	46	8	0.0	Sa	13.51	5.35	81.6
27- Site 2- P. 2- HB	1703	4.2	0	44.6	44	7.2	0.0	Sa	14.27	5.56	87.0
27- Site 2- P. 3- HA	1704	4.2	0	26.4	60	9.4	0.0	Sa	8.62	3.70	49.2
27- Site 2- P. 3- HB	1705	4.2	0	37	50.84	8	0.0	Sa	11.85	4.75	71.1
27- Site 2- P. 4- HA	1706	4.2	0	27.6	57.4	10.8	0.0	Sa	9.38	4.08	53.0
27- Site 2- P. 4- HB	1707	4.2	0	33.6	53.2	9	0.0	Sa	10.97	4.51	64.6

Appendix 8: Non-structural carbohydrates storage analysis

Taproots carbohydrate storages; sugars and starch extraction results from Caprivi State Forest and Okongo and Ncumcara Community Forests.

	Extract/ Fraction	**80%EtOH (Ethanol) extract**	**Water extract**	**Starch-enzyme digest**		
	Instrument used	**spectro-photometer**	**spectro-photometer**	**HPLC**		
	What was measured	**"total sugars"**	**"total sugars"**	**"total Glucose"**		
	expressed as:	**total sugars as % of Dry Weight (DW)**	**total sugars as % of Dry Weight**	**total glucose as % of Dry Weight**		
	Type of Carbohydrate	**NON-Starch**	**NON-Starch**	**Starch**		
	Type of Carbohydrate	**water soluble**	**water soluble (polysaccharides)**	**Starch**		
	Data below					
	Batch no: 27					
C	Farm or Location: Zambezi, Caprivi (C) State Forest			EtOH	Water	Starch digest
EAR lab#	**Sample numbers:**	**Sample numbers:**	**EAR lab#**	**%DW sugar Ethanol**	**%DW sugar Water**	**%DW starch**
1B	1. C-1.1 <250, 250, 425-600 B	1. C-1.1 B	**1B**	3.8	4.8	11.4
1T	1. C-1.1 <250, 250, 425-600 T	1. C-1.1 T	**1T**	4.1	3.8	12.4
2	2. C-1.2 <250, 250, 425-600	2. C-1.2	**2**	5.2	5.6	12.6
3	3. C.1.3 <250, 250, 425-600	3. C.1.3	**3**	3.6	5.0	14.9
4	4. C-1.4<250, 250, 425-600	4. C-1.4	**4**	4.7	4.7	**11.4**

EAR lab#	Sample numbers:	Sample numbers:	EAR lab#	%DW sugar Ethanol	%DW sugar Water	%DW starch
5B	5. C-1.5<250, 250, 425-600B	5. C-1.5 B	**5B**	4.7	4.7	12.4
5T	5. C-1.5<250, 250, 425-600 T	5. C-1.5 T	**5T**	5.6	5.2	10.2
6	6. C-1.6<250, 250, 425-600	6. C-1.6	**6**	4.4	6.8	14.4
7B	7. C-1.7<250, 250, 425-600 B	7. C-1.7 B	**7B**	4.9	5.0	10.6
7T	7. C-1.7<250, 250, 425-600 T	7. C-1.7 T	**7T**	4.5	4.9	11.6
8	8. C-1.8<250, 250, 425-600	8. C-1.8	**8**	5.1	5.5	11.3
9	9. C-2.1<250, 250, 425-600	9. C-2.1	**9**	5.0	5.0	12.5
10	10. C-2.2<250, 250, 425-600	10. C-2.2	**10**	3.9	6.5	13.1
11	11. C-2.3<250, 250, 425-600	11. C-2.3	**11**	3.5	6.3	18.6
12	12. C-2.4<250, 250, 425-600	12. C-2.4	**12**	4.5	5.8	17.4
13	13. C-2.5<250, 250, 425-600	13. C-2.5	**13**	4.6	4.3	10.2
14	14. C-2.6<250, 250, 425-600	14. C-2.6	**14**	4.5	5.3	11.5
15	15. C-1.A <250, 250, 425-600	15. C-1.A	**15**	4.6	6.3	13.3
16	16. C-2.A <250, 250, 425-600	16. C-2.A	**16**	4.8	4.7	15.6
17	17. C-3.A <250, 250, 425-600	17. C-3.A	**17**	4.9	7.9	12.7
	Batch no: 28					
N	Farm or Location: Kavango West, Ncumcara (N)					
	Sample numbers:	**Sample numbers:**	**EAR lab#**	**%DW sugar Ethanol**	**%DW sugar Water**	**%DW starch**
101	1. N-1.1 <250, 250, 425-600	1. N-1.1	**101**	3.8	4.9	15.0
102	2. N-1.2 <250, 250, 425-600	2. N-1.2	**102**	5.6	3.7	13.3
103	3. N-1.3 <250, 250, 425-600	3. N-1.3	**103**	6.0	4.9	11.3
104	4. N-1.4<250, 250, 425-600	4. N-1.4	**104**	5.7	6.2	16.4
105	5. N-1.5<250, 250, 425-600	5. N-1.5	**105**	3.6	7.7	17.4
106	6. N-1.6<250, 250, 425-600	6. N-1.6	**106**	4.8	6.6	20.8
107	7. N-1.7<250, 250, 425-600	7. N-1.7	**107**	4.1	5.0	11.5
108	8. N-1.8<250, 250, 425-600	8. N-1.8	**108**	4.3	5.1	21.7

	Sample numbers:	**Sample numbers:**	**EAR lab#**	**%DW sugar Ethanol**	**%DW sugar Water**	**%DW starch**
109 B	9. N-1.9<250, 250, 425-600 B	9. N-1.9 B	**109 B**	4.0	3.5	13.8
109 T	9. N-1.9<250, 250, 425-600 T	9. N-1.9 T	**109 T**	3.2	3.8	18.8
110	10. N-2.1<250, 250, 425-600	10. N-2.1	**110**	5.3	4.2	13.9
111	11. N-2.2<250, 250, 425-600	11. N-2.2	**111**	4.3	6.3	24.5
112	12. N-2.3<250, 250, 425-600	12. N-2.3	**112**	7.3	5.6	12.9
113	13. N-2.4<250, 250, 425-600	13. N-2.4	**113**	5.4	7.3	26.2
114 B	14. N-2.5<250, 250, 425-600 B	14. N-2.5 B	**114 B**	5.5	4.3	16.4
114 T	14. N-2.5<250, 250, 425-600 T	14. N-2.5 T	**114 T**	7.3	9.2	17.2
115	15. N-2.6 <250, 250, 425-600	15. N-2.6	**115**	5.5	5.3	15.7
116	16. N-2.7<250, 250, 425-600	16. N-2.7	**116**	6.8	5.4	20.5
117	17. N-2.8<250, 250, 425-600	17. N-2.8	**117**	5.4	6.9	19.1
118	18. N-2.9<250, 250, 425-600	18. N-2.9	**118**	4.0	5.2	15.2
119	19. N-1.A<250, 250, 425-600	19. N-1.A	**119**	4.1	5.2	13.9
120	20. N-2.A<250, 250, 425-600	20. N-2.A	**120**	5.3	3.9	13.7
121	21. N-3.A <250, 250, 425-600	21. N-3.A	**121**	3.8	2.8	11.6
	Batch no: 29					
O	Farm or Location: Ohangwena, Okongo (O)					
EAR lab#	**Sample numbers:**	**Sample numbers:**	**EAR lab#**	**%DW sugar Ethanol**	**%DW sugar Water**	**%DW starch**
201	1. O-1.1 <250, 250, 425-600	1. O-1.1	**201**	8.2	5.0	13.9
202	2. O-1.2 <250, 250, 425-600	2. O-1.2	**202**	7.8	4.2	17.8
203	3. O-1.3 <250, 250, 425-600	3. O-1.3	**203**	6.8	5.0	13.6
204	4. O-1.4<250, 250, 425-600	4. O-1.4	**204**	5.3	5.3	19.6
205	5. O-1.5<250, 250, 425-600	5. O-1.5	**205**	4.8	4.2	15.2
206	6. O-1.6<250, 250, 425-600	6. O-1.6	**206**	4.2	2.6	4.2
207	7. O-2.1<250, 250, 425-600	7. O-2.1	**207**	7.9	7.1	19.9
208	8. O-2.2<250, 250, 425-600	8. O-2.2	**208**	6.6	5.5	24.5

EAR lab#	**Sample numbers:**	**Sample numbers:**	**EAR lab#**	**%DW sugar Ethanol**	**%DW sugar Water**	**%DW starch**
209	9. O-2.3<250, 250, 425-600	9. O-2.3	**209**	3.6	3.6	9.6
210	10. O-2.4<250, 250, 425-600	10. O-2.4	**210**	3.9	5.4	17.1
211	11. O-2.5<250, 250, 425-600	11. O-2.5	**211**	3.2	6.2	22.9
212	12. O-2.6<250, 250, 425-600	12. O-2.6	**212**	5.6	4.3	7.6
213	13. O-2.7<250, 250, 425-600	13. O-2.7	**213**	5.4	5.4	19.5
214	14. O-2.8<250, 250, 425-600	14. O-2.8	**214**	3.5	4.7	12.8
215	15. O-1.A <250, 250, 425-600	15. O-1.A	**215**	6.2	5.5	11.1
216	16. O-2.A <250, 250, 425-600	16. O-2.A	**216**	6.7	4.4	23.8
217	17. O-3.A <250, 250, 425-600	17. O-3.A	**217**	4.7	5.6	11.3

Appendix 9: Respondents opinions; question 4.2.10

Respondents opinions on the management operations that affect *Pterocarpus angolensis* development from sapling to bole tree stage

	Okongo	**Ncumcara**	**Caprivi**
Question	**Respondents (%)**	**Respondents (%)**	**Respondents (%)**
4.2.10.1). Absence of fire during one fire season			
No effect	0	0	0
Small effect	10	0	10
Medium effect	5	13	0
Large effect	85	87	90
4.2.10.2). Absence (or low levels of) of domestic livestock			
No effect	40	25	0
Small effect	5	0	5
Medium effect	5	0	5
Large effect	40	69	90
Unknown	10	6	0
4.2.10.3). Absence (or low levels of) game animals that browse the trees			
No effect	25	25	5
Small effect	5	0	0
Medium effect	5	6	5
	Okongo	**Ncumcara**	**Caprivi**

Question	**Respondents (%)**	**Respondents (%)**	**Respondents (%)**
Large effect	60	69	90
Unknown	5	0	0
4.2.10.4). Partial removal of competing vegetation in the neighbourhood of the tree (e.g. by harvesting or utilizing neighbouring trees or grasses).			
No effect	0	0	0
Small effect	0	0	0
Medium effect	100	13	10
Large effect	0	87	90
Unknown	0	0	0
4.2.10.5). Higher than average rainfall in a particular year			
No effect	5	0	0
Small effect	10	6	5
Medium effect	5	6	10
Large effect	70	88	85
Unknown	10	0	0