COMPARISON OF GROWTH RINGS OF *DICHROSTACHYS CINEREA* AND *SENEGALIA MELLIFERA* ALONG A RAINFALL GRADIENT: IMPLICATIONS FOR BUSH ENCROACHMENT IN A CHANGING CLIMATE

A THESIS SUBMITED IN FULFILMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE (BY THESIS)

OF

THE UNIVERSITY OF NAMIBIA

BY

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APRIL 2020

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ABSTRACT

Tree ring studies, known as dendrochronology, have been an important tool for studying climate variations since the beginning of 1900s. This is because the information preserved in tree rings of most tree species for many years serves as environmental archives for both abiotic and biotic factors, tools that can be used to monitor climate changes. This study was the first to compare the growth rings of *Dichrostachys cinerea* and *Senegalia mellifera* along a rainfall gradient to infer implications for bush encroachment in a changing climate. Rainfall gradient in this study was defined by three study sites namely; 1) John Alphons Pandeni Research Station (600 mm); 2) Farm Onyoka (450 mm) and 3) Farm Ebenhaezer (250 mm). Stem discs of different sizes of the two species were sampled from each site and polished for dendrochronological study. The growth rings of *D. cinerea* trees were substantially influenced by the amounts of site rainfall, but the growth rings of *S. mellifera* trees were not influenced by site rainfall. Therefore, *D. cinerea* is a better sensor and indicator of rainfall variability and climate shifts than *S. mellifera*, which tolerates dry climates as much as the wet seasons. However, the growth patterns of *D. cinerea* trees did not differ significantly along a rainfall gradient ($H = 4.256$, $df = 2$, $p = 0.119 > 0.05$). On the contrary, *S. mellifera* tree growth patterns differed significantly ($H = 42.366$, $df = 2$, $p = 0.000 < 0.05$). *Senegalia mellifera* trees from John Pandeni grew faster compared to the ones from Ebenhaezer and Onyoka. The study concluded that species response to climate change vary by geographical location, through the influence of complex interactions of various factors including rainfall. For further dendroclimatology studies in Namibia, site and species should be carefully selected to include species that are more sensitive to soil moisture

(rainfall) and/or other climatic factors. Steeper rainfall gradient should be investigated in order to fully understand site climate variability of the recent past and to enable future projection of the results using climate models.

Key words: Climate change**,** dendrochronology, *Dichrostachys cinerea*, Namibia, rainfall gradient, *Senegalia mellifera*.

PUBLICATIONS AND CONFERENCE PROCEEDINGS

Shikangalah, R., Mapani, B., Mapaure, I., Herzschuhd., U., **Musimba, A.,** & Tabares., X., 2020. Growth ring formation of *Dichrostachys cinerea* and *Senegalia mellifera* in arid environments in Namibia. Dendrochronologia, 59. 125661.

Mapani, B.S., Shikangalah, R.N., **Musimba, A.K** (**presenter**)., Mapaure, I., Herzschuh, U., and Tabares, X., 2018. The growth rings of *Dichrostachys cinerea* and *Senegalia mellifera* as proxies for climate modelling along a rainfall gradient: an example from Namibia. 19th ANNUAL WATERNET/WARFSA/GWP-SAsymposium, University of Zambia, Livingstone, Zambia 31 October – 02 November 2018.

Mapaure, I., **Musimba, A.K** (**presenter**), and Mukaru, W.C., 2016. Effects of rainout sheltering on soil moisture and seedling numbers over a growing season in a selected camp of Neudamm farm, Namibia. 3rd International Global Change Conference, University of Kwazulu-Natal, Durban, South Africa, 5-8 December 2016.

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ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of variance
AWI	Alfred Wegner Institute
BMBF	Federal Ministry of Education and Research
Ca	Atmospheric Carbon
CCF	Cheetah Conservation Fund
Ci	Internal Carbon
CO_2	Carbon dioxide
DAAD	Deutscher Akademischer Austausch Dienst
DRFN	Desert Research Foundation of Namibia
ENSO	El Nino Southern Oscillation
FAO	Food Agriculture Organisation
GDP	Gross Domestic Products
GHG	Greenhouse Gasses
IADF	Intra-annual Density Fluctuations
IPCC	Intergovernmental Panel on Climate Change
MAWF	Ministry of Agriculture, Water and Forestry
MET	Ministry of Environment and Tourism

MSN	Meteorological Services of Namibia
NASA	National Aeronautics Space Administration
NOAA	National Oceanic and Atmospheric Administration
OPTIMASS savannah	Option for sustainable geo-biosphere feedback management in system under regional and glomal change
SADC	Southern African Development Community
SPSS	Statistical Package for Social Science
USAID	United States Agercy International Development
WPP	Waterberg Plateau Park
WUE	Water Use Efficiency

ACKNOWLEDGEMENTS

I would like to express my appreciation to many people and organisations for their help in the success of this work. Above all, I would thank Jehovah my God for making everything possible for me in life and brought me this far by caring and guiding me throughout my study.

I acknowledge the University of Namibia for making my study possible. I am grateful to the Biological Sciences Department for allowing me to use the laboratory in order to do the laboratory work of this study. My deepest gratitude goes to my main supervisor, Professor Isaac Mapaure for his guidance and constructive comments during the course of my study. I highly acknowledge my co-supervisors, Professor Benjamin Mapani and Dr Rosemary Shikangalah for their academic help and guidance during my thesis write-up and for stem disc processing and ring width analysis on WinDENDRO software, it was not easy but with your help it was possible. Many thanks to Dr Heinrich Ingo and Ms Jacobsen Inga for helping me with tree ring cross-dating in COFECHA and for teaching me dendrochronological rules for my study.

All rainfall data were provided by the Meteorological Services of Namibia, the author highly acknowledges their assistance. This study could not have been completed without the financial assistance from BMBF. It was funded by the Federal Ministry of Education and Research (BMBF) of Federal Republic of Germany through "Options for sustainable geo-biosphere feedback management in Savanna systems under regional and global change" (OPTIMASS) Research Project. My stay at The University of Potsdam, Germany was funded by the Deutscher Akademischer Austausch Dienst (DAAD), which I highly acknowledge.

I thank the University of Potsdam for giving me a space to do my research during my stay in Germany. Dr Heike Wanke, helped me in many ways so I can keep moving forward with my Masters. I highly acknowledge her generosity and kindness, for the time and effort she invested to help me with my travelling arrangements to and from Germany. Many thanks to Professor Ulrike Herzschuh for accommodating me at Alfred Wegner Institute (AWI) to do my data processing and analysis. Many thanks to Dr Ximena Tabares and Dr Dirk Lohmann, you helped me a lot during my stay at AWI.

I would like to thank Ms Charline Kamburona and her team for helping with tree sampling from John Pandeni Research Station and Farm Onyoka, it was not easy but you assisted. Mr. Gabriel Nghikongelwa, Ms Cecilia Ndunge, Mr Bernhard Shaduka and Mr Matthew Ndamona, thank you very much for all the immense support during the fieldwork. Cutting the trees especial *Dichrostachys cinerea* with a bow saw was not easy, but with your help, I got tree samples from Ebenhaezer for my study.

This study could not have been completed without the specimens export permit. My deepest gratitude goes to the Ministry of Agriculture, Water and Forestry for awarding me the export permit to get the tree discs for this study to The University of Potsdam, Germany.

I thank my family, my wife Ester Musimba and my son, Rafael Musimba for giving me reasons to do this Master's thesis and for being by my side during the write-up of this thesis. Thank you for your support and love you gave me, it really gave me courage and strength to finish the study.

My deepest gratitude goes to my friends and anyone else who helped me in one way or another and I have not personally mentioned them, your help brought me this far with my thesis, thank you very much. I love you so much!

DEDICATION

This thesis is dedicated to my son, Rafael Musimba whose birth in 2018 during my final year brought me an extra-ordinary joy, and to my late Father, Captain Rafael Musimba, a man who loved his family so much. Thank you for your good examples in life, encouragements and suport you gave me throughout my life, Father. You are my hero. When I was a boy, I thought you were an abusive man to me, untill I am a fully grown up man I realise that you really taught me well to be a very strong man in life, someone others can rely on and for that I appreciate it so much, Father.

DECLARATION

I, Aansbert Kudumo Musimba, hereby declare that this study is my own work and is a true reflection of my research, and that this work, or any part thereof has not been submitted for a degree at any other institution.

..... Date .....

Aansbert K Musimba

CHAPTER 1: INTRODUCTION

1.1 Background of the study

Climate change is a major global challenge to all living organisms and ecosystems, whether terrestrial or aquatic (Michelle et al., 2012; Singer & Parmasan, 2010; Wenger, 2010). This has led scientists from different disciplines of study around the world to try to understand climate change (Scafetta, 2010; Worbes, 2002; Graedel & Crutzen, 1993). Climate change is believed to be caused by Greenhouse Gasses (GHGs) such as carbon dioxide, sulphur hexafluoride, perfluorocarbon and methane which are caused by both natural and anthropogenic factors (Cicerone & Nurse, 2015). Among the gasses in the atmosphere, carbon dioxide and oxygen are the two gasses that are most exchanged between the atmosphere, the oceans, terrestrial biosphere and more slowly with sediments and sedimentary rocks (Stoffel & Bollschweiler, 2010; Harold et al., 1999). The GHGs trap heat radiated from the earth, therefore increasing the concentration of GHGs in the atmosphere leads to warming earth as the trapped heat will be reflected back to the earth by the GHGs (Cicerone & Nurse, 2015). There is scientific consensus that concentrations of greenhouse gases in the atmosphere are increasing and they are the cause of global climate change (Cicerone & Nurse, 2015; Venkataramanan & Smitha, 2011).

The significant changes that are occurring on Earth, include increasing air and ocean temperatures, widespread melting of glaciers, snow and ice, rising sea levels, high heat waves, increasing frequency of flood and droughts (Kevin, 2017; Shah & Shah, 2014). Detailed knowledge about the variability of physical and chemical processes driving

global systems may be obtained from natural archives (e.g. trees, ice cores and sediments), which have been able to preserve a signature of major parameters like temperature, rainfall patterns, carbon dioxide and nitrogen concentration in the atmosphere (Chhetri & Shrestha, 2014; Graedel & Crutzen, 1993).

The need for advanced studies on climate change in Namibia has been outlined (Zeidler, Kandjinga & David, 2010). Namibia is situated on the south western part of Africa. The climate is generally hot and dry with sporadic rainfall (Ministry of Environment and Tourism (MET), 2010). More than ninety percent of the land total is either hyper-arid, arid or sem-arid and rainfall is extremely variable in space and time (MET, 2008). Due to climate change, Namibia is experiencing unpredictable drought and floods, high heat waves and high evaporation rates (Zeidler, Kandjinga & David, 2010). Rainfall shows a decreasing trend from north-east toward north-west then to the south (Nesongano, 2018; de Klerk, 2004; Mendelsohn et al., 2002). Regarding trends of climate in Namibia, studies of its history are limited (Midgley et al., 2005). There is clear evidence that there have been changes in atmospheric circulation and that the character of rainfall has changed inappreciably (Hulme, 1996). Although the past trends are no guarantee of future change, they are valuable as they are the foundation from which to judge current adaptation strategies to climate change and how they may be appropriate for a given future expected change (Hulme, 1996). They provide a context within which to understand the key processes that cause changes at the local scale (Bhugeloo, 2014).

The scientific study of tree rings, also known as dendrochronology, which is both an old and modern science has been a remarkable tool in understanding climate change as trees record environmental and site conditions for thousands of years (Gebrekirstos et al., 2014; Worbes, 2002; Graedel & Crutzen, 1993). Trees are good environmental

monitoring tools as they record the environmental conditions that limit their biological process (Harold et al., 1999). As trees grow, they add new layers of wood to their trunks each year (Chhetri & Shrestha, 2014; Sheppard, 2010). Since the trunks of trees are round, this new growth is called a growth ring or tree ring (Garcia-Suarez, Butler & Baillie, 2009). These rings show the amount of wood produced during one growing season and are influenced by local environmental conditions (Andreu, et al., 2007). Moreover, tree rings provide clues to long term weather patterns, and/or climate up to thousands of years (Stoffel & Bollschweiler, 2010). Tree rings also record low and high frequency weather patterns at scales of centuries, decades and seasons (Garcia-Suarez, Butler & Baillie, 2009). Therefore, this makes trees a potential tool for obtaining information about age, growth rate and age related yield of trees, as they record information on past and present and provide clues of future climatic changes (Kevin, 2017; Verheyden et al., 2004). Furthermore, every ring of any tree can be dated to a certain growing period or to a calendar year (Worbes, 2004). Ring patterns in trees are the mirror of the growth conditions of a tree (Matthew et al., 2015; Worbes, 2002). The rings and their features represent an archive of growth conditions during a tree's life (Büntgen & Tegel, 2011). Many studies have shown that the rings integrate information about environmental factors influencing photosynthesis, transpiration and wood accumulation and store information about temporal and spatial dynamics of climate change and the hydrological and carbon cycles (e.g. Kevin, 2017; Rinne, Alestalo, & Franke, 2016; Bhugeloo, 2014; Buntgen et al, 2007). Very old trees are more interesting because they provide clues of what the climate was like before measurements were recorded (National Aeronautics and Space Administration (NASA), 2008).

Different studies have shown that distinct tree rings occur only in tropical and temperate regions (e.g. Mann, Hughes, Cook & Esper, 2002). Nevertheless, studies of high resolution stable carbon and oxygen isotope ratio for woody trees have shed light into the field of dendrochronology (Mahecha, 2015). Stable isotope of carbon and oxygen ratios of tree rings have proven to be a valuable indicator of environmental conditions (including climate change) in tropical regions (Mahecha, 2015; Verheyden et al., 2004). Several similar studies based on stable isotopes of carbon and oxygen showed that oxygen isotope composition of the xylem sap indicate the water source utilised by a tree during a specific time in the past (e.g. Nock, Metcalfe & Hietz., 2016; Xing et al., 2012; Mckee et al., 2002; Lin & Sternbeg, 1999). Similarly, in the temperate regions the use of both tree rings and stable isotope can be a useful tool for climate change studies (Mahecha, 2015).

Modern tree ring information records of isotopes and ring patterns can be used to compare with local instrumental measurements (Sheppard, 2010). In most countries, daily weather records have only been kept for the last 100 to 150 years, thus, to learn about the climate hundreds to thousands of years ago, scientists need to use other sources such as trees, corals and ice cores (NASA, 2008; Grudd, 2006).

A number of plant species in Southern Africa have been shown to be remarkable tools for climate change studies, including a number of *Vachellia*, *Senegalia* and *Terminalia* species as well as *Dichrostachys cinerea* (Bhugeloo, 2014; Gourlay, 1995a & b). Therefore, in this study two different encroaching woody plant species, *D. cinerea* (Wight & Arnott, 1965), and *S. mellifera* (Dyer, 2014) were investigated to see if we could obtain information about climate change, which should be recorded in their tree

trunks. with samples collected at three different sites along a rainfall gradient to represent climate change in Namibia.

1.2 Statement of the problem

Climate change has become a major problem, impacting water resources, agricultural and food systems in Southern Africa, particularly Namibia (Adhikari et al., 2015). Climate change is also increasing the strength of floods, droughts and evapo-transpiration each year from the north to the south of Namibia (Zeidler, Kandjinga & David, 2010). The Southern African countries experience at least three droughts every ten years mainly due to El Nino Southern Oscillation (ENSO). There is yet no unanimity about the intervals of drought frequency in the Southern Africa, especially Namibia which is situated on the cold Benguela Current of the Atlantic Ocean (Chagutah, 2010).

With all practical measures that have been taken to minimize the spread of encroaching woody plants, the problems caused by *D. cinerea* and *S. mellifera* are still common (Cheetah Conservation Fund (CCF), 2017). Although studies have been done on the two encroaching species, there is yet no full understanding of their adaptation to the changing climate despite the problems they pose are advancing appreciably (CCF, 2017).

The high density of these two species impacts adversely on biodiversity, water-use efficiency and underground water tables, thereby contributing to the process of desertification (Joubert, 2014; de Klerk, 2004). Bush thickening is seen as a major

threat to the botanical diversity and is having negative impacts on sustainable livestock production and settlement, especially in rural areas (Joubert, 2014; Kambatuku, 2010; de Klerk, 2004).

1.3. Objectives

The overall objective of this study was to compare the growth rings of *Dichrostachys cinerea* and *Senegalia mellifera* along a rainfall gradient to infer implications for bush encroachment in a changing climate. The specific objectives were therefore, to**:**

a) Determine whether rainfall gradient influences the width of growth rings in *Dichrostachys cinerea* and *Senegalia mellifera*;

b) Determine the formation and characteristics of distinctive growth rings in *D. cinerea* and *S. mellifera*;

c) Determine the relationship between stem diameter and xylem diameter in *D. cinerea* and *S. mellifera* along a rainfall gradient;

d) Determine the relationship between the numbers of growth rings and stem diameter of the two species along a rainfall gradient; and

e) Compare the tree ring growth patterns between the two species along a rainfall gradient, and infer survival strategies of the two species.

1.4 The hypotheses were:

a) Rainfall gradient does not influence the width of growth rings in *Dichrostachys cinerea* and *Senegalia mellifera*;

b) Both *D. cinerea* and *S. mellifera* form distinctive growth rings;

c) There is no relationship between stem diameter and xylem diameter in *D. cinerea* and *S. mellifera* along a rainfall gradient;

d) There is no relationship between number of growth rings and stem diameter in *Dichrostachys cinerea* and *Senegalia mellifera* along a rainfall gradient; and

e) The two species show no differences in their ring growth patterns along a rainfall gradient.

1.5 Significance of the study

There are very few or no quantitative or qualitative indicative study of how climate change is occurring in Namibia. Climate change has a wide spread impact on multiple scales of biodiversity including genes, species, communities and ecosystems (Xing et al., 2012). This study is significant as it contributes to the understanding of climate change in Southern Africa, in particular Namibia, through the use of tree rings. This study of tree rings growth on *D. cinerea* and *S. mellifera* adds value to the current understanding and refining of Global Climate Models (GCMs). Answering some of the climate change questions helps the stakeholders to plan for climate change adaptation strategies especially, farmers and the water resource managers. The knowledge of

drought and flood frequency, as recorded in tree rings, helps farmers to make plans for droughts in advance and guides citizens in Namibia regarding their settlement decisions.

Knowing the growth and survival strategies of the two encroacher species improves the management of bush density caused by the two invader species and this contributes toward Namibia's Vision 2030 and the UN Sustainable Development Goals (SDGs), particularly SDG 13 (Climate action) and SDG 15 (Life on land).

1.6 Limitation of the study

The study focused on rainfall as the main source of precipitation and biotic and abiotic environmental conditions that affect the growth and survival of these two species. Literature has shown that climate change occurred in the last 60 years (Cicerone & Nurse, 2015; IPCC, 2014). Therefore in our sampling procedure, one limitation could be obtaining trees that are much younger than this age. Rings of the two species were too small for proper isotope study, which could otherwise have contributed to the understanding of how atmospheric carbon dioxide contents have changed along a rainfall gradient in Namibia.

CHAPTER 2: LITERATURE REVIEW

2.1 Global climate change

Climate change is any systematic and statistically significant change in the long term statistics of climate elements such as precipitation, temperature, pressure or winds, sustained over several decades or longer (Cicerone & Nurse, 2015; NASA, 2008, National Oceanic and Atmospheric Administration (NOAA), 2007). Climate change can be caused by different natural external factors such as changes in the emission of solar radiation or slow changes in the Earth's orbital elements, natural internal processes of the Earth's climate system, or by anthropogenic factors such as an increase in the concentration of greenhouse gases, deforestation or combinations of these factors (Intergovernmental Panel on Climate Change (IPCC), 2018; Cicerone & Nurse, 2015). According to IPCC (2014) there is more than enough observational evidence from all continents and most oceans that the global climate is changing.

It is now more certain than ever, based on many lines of evidence that humans are changing the earth's climate (Coetzee, 2010). Since the beginning of industrial revolution, human activities, mainly the burning of fossil fuel has increased the concentration of Greenhouse Gasses (GHGs) such as carbon dioxide and methane (Cicerone & Nurse, 2015). According to Davis (2011), GHGs occur naturally in a low concentrations. However, Davis (2011) explained that since industrial revolution, substantially high levels of GHGs have been detected and attributed to human activities. An increase of 40% of atmospheric CO_2 has been recorded from 1900 to 2012 which has led to an increase in global surface temperature with a likely range

between 0.8 °C and 1.2 °C (IPCC, 2018; Cicerone & Nurse, 2015). Global warming has been accompanied by warming of the ocean, sea level rise and a strong decline in Arctic Sea ice, and many other associated climate effects (Venkataramanan & Smitha, 2011). Much of this warming has occurred in the last six decades (Cicerone & Nurse, 2015; IPCC, 2014).

The long term climate change will mainly depend on the total amount of greenhouse gases, mainly, carbon dioxide emitted as a result of human activities (Kaddo, 2016). Continued emissions of these gases will cause further climate change, including substantial increases in global average surface temperature and important changes in regional climate (Cicerone & Nurse, 2015).

Several studies have pointed out that climate change affects the strength and frequency of floods, droughts, hurricanes and tornadoes in different regions of the world (e.g. Pearl, Anchukaitis, Pederson & Donnelly, 2017: Davis, 2011; Eriksen, O'Brien & Rosentrater, 2008). The lower part of the earth's atmosphere is becoming warmer and moist as a result of greenhouse gases increase in the atmosphere (NOAA, 2007). NOAA (2007) added that this will likely give more energy for storms and certain severe weather events. Heat waves and heavy rainfall and snow (which cause floods) are becoming even more frequent in some part of the world (Pearl et al., 2017).

The impacts of climate change affect natural environment, economies and society (Reid et al., 2007). The same authors added that widespread changes in regional and local temperature and precipitation as well as with increase in some types of extreme weather events such as sea level rise and storm surge will have serious impacts on

human societies and the natural world. Rainstorms have become heavier, wet regions have become wetter and dry regions have become drier and all these events are threatening food production, fresh water availability and the welfare of the huge population currently living in low-lying areas of the world (Masih et al., 2014; Eriksen, O'Brien & Rosentrater, 2008). However, trends in extreme weather vary from region to region (Davis, 2011).

According to Michelle et al. (2012), climate change is having a wide spread impact on multiple scales of biodiversity including genes, species, communities and ecosystems. Biological response to climate change varies widely among species and populations (Michelle et al., 2012). Michelle et al. (2012) added that some species response on climate change are positive while other species response are negative. This has led to location or wide spread decline, and many species are shifting their geographical ranges in response to rapid change in temperature and precipitation regime in the world (Michelle et al., 2012).

Climate change has both direct and indirect effects on ways species interact over spatial and temporal scale, which is a profound impact on ecosystem structure and function (Singer & Parmasan, 2010; Wenger, 2010). According to Yang & Rudolf (2010) high temperature due to climate change affects food web interaction by increasing total rates such as growth and consumption globally.

According to IPCC (2018), reducing global warming from 2°C to 1.5°C can have a tremendous positive effects on many different parameters affected by climate change grobally. The same study further stated that limited global warming of 1.5°C can reduce ocean temperature as well as associated increases in ocean acidity and

decreases in ocean oxygen levels. Besides that, the author stated that limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries and ecosystems, as well as their functions and services to humans. Climate-related risks to health, livelihoods, food security, water supply, human security and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C (IPCC, 2018).

2.2 Climate change in Southern Africa

Southern African countries emit very little amounts of GHGs compared to other regions on the globe, like Asia, Europe and North America yet they experience the worst of global warming (United States Agercy International Development (USAID), 2011). There is much evidence that Africa's average temperature is warming faster than the global, and this will likely continue (Conway, 2008; Eriksen, O'Brien & Rosentrater, 2008). According to the 21 Atmosphere-Ocean General Circulation Models analysed by the IPCC (2007; Conway, 2008) over the next 100 years, the northern and southern regions of Africa will likely become hotter (as much as 4 °C or more).

A study done by Davis (2011) on climate risk and vulnerability described Southern African region as predominantly semi-arid with intra seasonal and inter-annual rainfall variability. Davis (2011) added that Southern Africa's climate is warming up and that much of the region experience an average annual temperature above 17 °C due to the changing climate. The mean annual temperature in Southern Africa is projected to rise by 2 to 5°C by 2050 while precipitation will likely decrease by 15 %

in the western and southern part (IPCC, 2014; 2007). High warming rate is expected over the semi-arid Southern African countries, especially north western South Africa, Botwana and Namibia (IPCC, 2014).

Climate change is having immediate and long term impacts on water (Arnell, 1999). These including flooding, drought, sea-level rise in estuaries, drying up of rivers, poor water quality in surface and groundwater systems, precipitation and water vapour pattern distortions (Urama & Ozor, 2010; Arnell, 1999). In regions of seasonal drying in the Southern Africa there are changes in the total amount of rainfall and rainfall patterns (Bauer & Scholz, 2010). For example, there is a proportionally larger decrease in the number of rain days, but with greater intensity of rainfall (Mapaure, 2011; Conway, 2008). Conway (2008) further explained that floods could become common in Southern Africa as some regions will experience high rainfall, even in drier regions there is likely to be a higher frequency of more intense of rainfall, which may create flooding. The Southern African region has experienced droughts both in short and long term (England, Dougill, Stringer, & Vincent, 2016; Giovanna et al., 2009). Some rivers and lakes are in the process of getting dry and are experiencing very low flow (e.g. Zambezi River) due to climate change which is affecting precipitation systems (England et al., 2016; Beilfuss, 2012). According to Conway (2008) water shortage due to climate change in Southern Africa is affecting agricultural, industrial and energy sectors, hydrological communities and the needs of the environment. According to Brekke et al. (2009) climate change has the potential to affect many sectors in which water resource manager plays an active role. Brekke et al. (2009) further stated that this include water availability, water quality, flood risk

reduction, ecosystem, coastal area hydropower and other energy sector and the major drivers are precipitation and temperature. In general, high precipitation results in more water available which causes floods at some area, and low precipitation and drought reduces water supply (http//www.sws.uiuc.edu/climate/climate factors.asp). High temperature causes a greater amount of water loss from earth surface to the atmosphere (http//www.sws.uiuc.edu/climate/climate factors.asp).

According to Jury (2013), fluctuating climate of Africa is governed by marine and continental interactions. Most countries in the Southern region experience three droughts every ten years mainly due to changes in the phases of the El Niño-Southern Oscillation (ENSO) phenomenon and periodic sea surface temperature changes (Chagutah, 2010). The El Nino related droughts, are negatively impacting the inhabitants and economies of the Southern Africa region, further lamented by Chagutah (2010). Drought events result in crop losses and death of cattle herds that subsequently lead to widespread of food shortage (Southern African Development Community (SADC), 2010). For example, the consecutive dry spells of 2001 and 2002 caused by El Nino in the Southern African region affected more than six countries, namely Lesotho, Malawi, Mozambique, Swaziland, Zambia, Zimbabwe and Namibia. These faced a food deficit of about 1.2 million tonnes of cereals and non-food requirements (SADC, 2010).

2.3 Climate change in Namibia

Namibia contributes very little to GHGs emission, and is estimated to be a net carbon sink, yet one of the most vulnerable countries to the effects of climate change in the

sub-Saharan Africa (Mapaure, 2011; Coetzee, 2010). Due to the aridity nature of Namibia, the country is very vulnerable to climate change effects (Mapaure, 2011). Mapaure (2011) further noted that intense flooding, shortening of the growing season, more frequent droughts, rising average summer and winter temperatures, among others are evidence of climate change impacts in Namibia. In the study on the economic impact of climate change in Namibia, Reid et al. (2007) noted that temperature in Namibia has been increasing at three times the global mean temperature. Reid et al. (2007) further remarked that the temperature prediction for 2100 for Namibia ranges from 2 to 6°c, particularly in the central regions. The same author added that lower rainfall is expected while overall rainfall is projected to be more variable than it is at present time.

A study by the Desert Research Foundation of Namibia (DRFN) and the Climate Systems Analysis Group of the University of Cape Town (MET, 2008), noted that Namibia will heat up to an alarming extent; most of the country will experience an increase of at least 2 °C, but up to 3°C (and even 4°C in some areas) in both winter and summer minimum, mean and maximum temperatures by the middle of this century. The study further noted that the situation will be more complex and ambiguous in the case of expected changes in rainfall but there is general agreement between models that the growing season will start later, end sooner and thus be shorter in most parts of the country. Individual rainfall events will be heavier while extreme floods and droughts will be frequent (England et al., 2016; Mapaure, 2011; Bauer & Scholz, 2010).

Namibia will be hit mostly by climate change effects than other most countries in Africa (Mapaure, 2011). Close to 70% of the inhabitants dwell in rural areas and directly depend mostly on ecosystem goods and services (Mapaure, 2011). Due to climate change, the variability of year-to-year rainfall has become extremely high, and that is "30% everywhere in the country, rising to 70% in southern Namibia and 100% in the Namib Desert", reported by Mapaure (2011). People from Ohangwena Region reported variability in rainfall patterns characterised by high intensity rainfall over a shorter period of time, late coming of the rain, quick disappearance of surface water, less cold winters than before and much stronger and hotter summer sun (Mapaure, 2011; Nunes et al., 2010). These trends in rainfall and temperature patterns, observed by communities in northern Namibia, were confirmed through trend analysis of the period 1900 to 2000" by Mitchell et al. (2004; Mapaure, 2011). According to Midgey et al. (2004) these trends in rainfall and temperature patterns will impact the Namibia's economy since agricultural activities which depend on rain water contribute more to the country's Gross Domestic Products (GDP).

2.4 Tree rings as proxy indicators for climate change

Trees monitor environmental conditions that affect their biological processes and all this information is stored in their ring structures (Breitenmoser, Brönnimann & Frank, 2014). This information is a valuable proxy for climate change studies on a regional scale (Nock, Metcalfe & Hietz., 2016; Novak et al., 2013; Steenkamp et al., 2008). Tree rings are influenced by climate conditions and they show distinct episodes of moist and dry periods for over time (Novak et al., 2013). The number of tree rings

provide information about the tree age; however they also provide other information such as fire events, drought and severe storms (Xing, Zhang & Baker, 2012). Besides that, Feliksik & Wilczyński (2009) noted that, apart from these conditions, tree rings also record other ecosystem events such as insect outbreak and logging.

Tree ring analysis can be used to reconstruct and draw conclusions about precipitation patterns over past periods at regional, hemispheric or even global scales (Zhang, 2015; NASA , 2008). Therrell et al (2006) did a study of tree-ring to reconstruct rainfall variability in Zimbabwe using *Pterocarpus angolensis*. Their study found a significant correlation between regional chronology and summer rainfall (November–February) from 1901 to 1948, and this explained a reconstruction of 46% of the instrumental rainfall variance during this period. The same author noted that reconstruction was well correlated with indices of the El Nino-Southern Oscillation (ENSO). According to Zhang (2015) precipitation information in tree-rings can help us to better understand climate behaviour and its mechanisms in the past and then predict variation trends for the future.

Verheyden et al. (2004) explained that tree rings record the temporal and dynamic of change in atmospheric carbon dioxide, water cycle and the physiological responses to these changes. Verheyden et al. (2004) further explained that the ring proxies such as ring width, ring density and stable isotopes content record variations of air temperature, relative humidity and precipitation through physiological responses to these environmental conditions indirectly. Li, Harrison, Prentice & Falster (2014) also explained that tree ring width may vary every year depending on variation in local temperature and precipitation. Li et al. (2014), stated that the growth of tree rings in

some tree species is mostly controlled by temperature and the growth of rings in some other trees are mostly controlled by precipitation. However, they concluded that general tree growth rings are controlled both by precipitation and temperature and other environmental conditions that may affect the trees.

Feliksik & Wilczyński (2009) noted that when the conditions in a particular year are good, the trees grow faster and invest more tissue material for that year's ring. However, if the conditions for a subsequent or particular year are poor, the trees grow slowly and invest less woody material, hence the rings would become narrower. Tree rings record past climate conditions because their width is determined by growth rates which are also determined by environmental conditions (Mahecha, 2015; Worbes, 1995). According to Worbes (1995), the ring width of each year's layer reflects growing conditions such as temperature, sunlight and water availability. Feliksik & Wilczyński (2009) explained that, a wider ring indicates a good growing season while a narrower ring indicates poor growing conditions in the ecosystem.

Büntgen & Tegel (2011) stated that Southern hemisphere trees differ from those of the equatorial as some of the tree species [such as *Vachellia erioloba* (Steenkamp et al., 2008), *Pterocarpus angolensis* (Matthew et al., 2007, 2006; Stahle et al., 1999) and *Widdringtonia cedarbergensis*, February & Stock, 1998)] always grow annual rings and occur at a constant rate. February & Stock (1998) conducted a dendrochronological study in Algeria, Krakadouw and Die Bos, South Africa to determine the relationship between ring width measures and precipitation for *Widdringtonia cedarbergensis.* Their study found no sufficient correlations between *W. cedarbergensis* ring width indices and precipitation to reconstruct rainfall through

time. According to their conclusions, it was due to a lack of an abrupt termination of late wood growth in many of the trees they used for their study.

Xing et al. (2012) studied age and radial growth pattern of four tree species in a subtropical forest of China to examine the growth characteristics within and among the species. Fifty percent of the tree species collected showed visible and cross dated rings. However, they also found a lack of stable relationship between ages and stem diameter of *Pinus massoniana, Schima superba, Quercus serrata* and *Castanopsis eyrei*. In a study on the effect of climate on tree-ring chronologies of native and non-native tree species growing under homogenous site conditions in Brazil, Feliksik & Wilczyński (2009) detected the influence of precipitation and temperature on the diameter increment of all the investigated tree species (*Pinus sylvestris*, *Picea abies*, *Abies alba*, *Pseudotsuga menziesii* and *Picea sitchensis*). Among the investigated species, *P. sitchensis* was characterized by the widest mean tree-ring (3.09 mm), while the mean tree ring of *P. sylvestris* was the narrowest (2.11 mm) as it did not cope well with low rainfall and high temperature sites.

Fichtler et al. (2004) conducted a study along a rainfall gradient in northern Namibia (Katima Mulilo, 674 mm and Ondangwa, 454 mm) to determine climatic signals in tree rings of *Burkea africana* and *Pterocarpus angolensis*. They successfully cross dated radii between all trees and all showed distinct growth rings. Their main focus was on temperature and ENSO indices as climatic signals. However, Fichtler et al. (2004) found a positive growth response to rainfall for both tree species from both sites, although a time-lag in the reaction occurred between the sites, which corresponded to the time-lag of the beginning of the rainy season.

Steenkamp et al. (2008) conducted a study in South Africa, on age determination of *Vachellia erioloba* trees in the Kalahari. Their results showed a strong relationship (R^2 = 0.93) between annual ring count and radiocarbon dating. In addition, their research also detected a strong correlation (r = 0.74) between stem circumference and estimated age of *V. erioloba* by radiocarbon dating. Schubert & Jahrem (2015) did a similar study on seasonal temperature and precipitation recorded in the intra-annual oxygen isotope pattern of meteoric water and tree-ring cellulose. They affirmed that average intra-annual change in $\delta^{18}O$ across tree rings reflects average seasonal precipitation changes.

Natalini et al. (2016) conducted a study in southern and central Spain (annual rainfall, 520 mm) and Portugal (750 mm) to find out how tree rings of *Pinus pinea* reflect growth adjustments and among sites under climate change. They found similarities in tree ring growth and response to climate among sites, as growth of *P. pinea* trees in both sites were enhanced after precipitation during the previous autumn and the current spring, and was limited by water shortage. The same study concluded that radial growth of *P. pinea* indicated strong effects of climate change. A similar study by Ramming et al. (2015) on the coincidences of climate extremes and anomalous vegetation response by comparing ring patterns of 36 conifer tree species. They found that low precipitation combined with high temperature leads to reduced tree growth for both the current and the following year. Their study focused on multiple selected conifer species in the Mediterranean.

Novack et al. (2013) did a study on tree rings using *Pinus halepensis* woody plant species from three regions that receive different amounts of annual rainfall,

Guardamar (276.4 mm), Maigno (369.3 mm), Daraca (428.6 mm) and Slovenia (1027.4 mm). They found annual ring width difference from these different sites. *P. halepensis* had largest mean annual ring width of 3.73 mm and these from Guardamar were found to have the smallest mean annual ring width of 0.87 mm. Their study further explained that year-to-year ring width variation were related to climatic variation in winter and spring since radial growth of *P. halepensis* is highly dependent on climatic conditions during the growing season. The same author concluded that, difference in seasonal precipitation were the cause of annual ring width difference in *P. halepensis* from different four sites. Campelo et al. (2015) stated that tree ring width declines with tree age. The study by Campelo et al. (2013) found that larger trees (with wider rings) showed almost 15 % more intra-annual density fluctuations (IADFs) than smaller trees (with narrow rings). According to Campelo et al (2015) as trees get older they also get larger, and although rings tend to be narrower, a higher volume of wood is produced each year, affecting the water supply for transpiration, which in turn can change the response of tree growth to climate. However, distinct tree rings occur only in tropical and sub-tropical regions where rainfall is seasonal (Mann et al., 2002). Worbes (2002) stated that the gradual deceleration of tree growth in tropicals happen in autumn until cambial dormancy as a consequence of low temperature. This leads to the formation of latewood, which is structural different from the earlywood of the previous growing season. Worbes (2002) added that in the tropical climate, variation of annual temperature with near or below freezing point in winter and variation of precipitation between rain season and dry season are clearly marked in tree rings. According to Turney et al., (2014), in tropical Savannas, not all tree species grow at the same rate in the same environmental conditons. The longer-

lived trees grow slowly while the short-lived trees grow faster (Turney et al., 2014). For example, Turney et al. (2014) explained that Oaks will add very thin ring each year while Willows and Aspen, on the other hand, have a short life cycle but compensate with intense growth, their annual rings are wider.

In the southern hemisphere, Bhugeloo (2014) sampled trees ranging in age from 30 to 99 years in Kwazulu-Natal, South Africa to determine the relationship between tree ages and stem diameter. Bhugeloo (2014) found a strong positive relationship ($r = 0.811$) between tree age and stem diameter of *Vachellia nilotica.* The study targeted a specific larger stem diameter of *V. nilotica* and did not sample the stem diameter randomly. This failed the attempt of correlating the master chronology with instrumental climatic data in *V. nilotica* as the stem size did not relate to ring width and growth ring numbers. Growth of different individual trees species that occur under similar site conditions, are especially useful for climate change studies at a local level (Novak et al., 2013). In addition, in dendrochronology, investigations, searching for climate-tree growth relationships, the choice of trees of proper age are very important (Novak et al., 2013). According to Worbes (2002) since the climate influences all trees on a given stand equally, tree-ring patterns are similar between individuals of a stand. However, the degree of similarity depends on the distance between growing sites, the climatic variability in a region and the ecological range of a tree species. Worbes (2002) explained that the most important principle in dendrochronology is comparison of tree-ring patterns of different individuals at the same site and this requires different tools such as statistical methods for correlation.

Bhugeloo (2014) assessed the dendrochronological and dendroclimatological potential of *V. nilotica* (L.) in northern KwaZulu–Natal, South Africa. In the study, Bhugeloo (2014) performed a correlation analysis to determine the relationship between *V. nilotica* ring width and locally average climate data. The analysis results showed a weak mean sensitivity which suggests that *V. nilotica* was not strongly influenced by rainfall and temperature.

According to Verheyden et al. (2004) stable isotopes content in tree rings record variations of atmospheric gases such as carbon dioxide, oxygen, nitrogen, relative humidity and precipitation trough physiological response to these quantities indirectly. Ghosh & Brand (2003) explained that atmospheric ^{13}C of carbon dioxide has incerased over time, mainly due to addition of ^{13}C depleted fossil fuel. This isotope disequilibrium effect today renders the assessment of the relative contributions of respiration and photosynthesis to changes in atmospheric carbon dioxide difficult (Ghosh & Brand, 2003).

Verheyded et al. (2004) studied growth rings, growth ring formation and age determination in *R. mucronata* in Kenya. The main aim of the study was to determine the formation of stem layers in relation to prevailing environmental conditions as well as their potential for age determination of the tree. Their study used cambial marking and trees of known ages to determine the age of *R. Mucronata*. Their method was successful as it provided the information about changes in environmental conditions. Tognetti et al. (2014) used dendrochronological methods and dual-isotope analysis to investigate whether atmospheric changes enhanced water use efficiencies of *Fagus* and *Nothofagus* genera and tree growth in Italy and Chile. Their results showed a

continuous enhancement in water use efficiency (WUE) at all the sites, which were primarily related to changes in ambient carbon dioxide.

In a study on stable isotopes in tree rings as a proxy indicator for winter precipitation, Holzkämper et al. (2008) concluded that stable isotopes provide additional information of the limiting conditions during growth of trees in extreme environments. Even though they were interested in winter precipitation and not annual precipitations by comparing ^{13}C and ^{18}O, the results were clear in that there is a link between stable isotopes and winter precipitation. Incorporation of high resolution carbon and oxygen isotopes profile across tree rings quantify seasonal climate (Schubert & Jahrem, 2015). Schubert & Jahrem (2015) further explained that, average intra-annual change in ^{18}O across tree rings reflect average seasonal change and the seasonal change are affected by average seasonal climate change.

Tognetti et al. (2014) did a study on stable isotopes in tree rings. Their study results showed that tissue ^{13}C provides an integrative record of supply and demand for carbon dioxide. Tognetti et al. (2014) further explained that variation in ^{13}C may be driven by changes in stomata conductance (i.e., supply of CO_2), or in photosynthetic rate (i.e., demand for CO_2), or both. Stomata closure due to low water availability, generally reduces Ci, leading to an increase in ^{13}C. Therefore, the dependence of ^{13}C on the ratio Ci/Ca (Ci = internal carbon; Ca = atmospheric carbon) in plants provides limited information about the strength of stomata control of Ci and photosynthesis, since a change in ^{13}C could be the result of a change in either stomata conductance or photosynthesis (Garcı´a-Sua´rez, Butler & Baillie, 2009; Tognetti et al., 2014). Tissue ^{18}O is not strongly influenced by photosynthetic rate, so that combined measurements

of ^{13}C and ^{18}O should allow stomata and photosynthetic effects on ^{13}C to be teased apart and the relative responses of both ^{13}C and ^{18}O can be related to the sensitivity of a plant to changing evaporative conditions (Tognetti et al., 2014; Verheyden et al, 2004).

2.5 Dendrochronology challenges in Southern Africa

There are challenges doing dendrochronolical studies in the Southern Africa due to the problems of relating the rings to the ages of plants and to climate in many tree species in tropical and subtropical regions (Bhugeloo, 2014; February et al., 2006; LaMarche, Holmes, Dunwuddie & Drew, 1979). February et al. (2006) stated that, tree ring studies in Southern Africa are somehow limited as many tree species in subtropical and tropical regions lack annual rings. Similar study by Jones et al. (2009) agreed that, dendrochronology in the Southern hemisphere has not been widely researched due to the perceived lack of annual growth rings in tropical and subtropical tree species. Many of woody species in the Southern Africa do not live long and show little ring-width variation (Bhugeloo, 2014; LaMarche et al., 1979). The same author states that, for some species, there is no assurance that the rings are annual (Bhugeloo, 2014). Therefore, this would have to be carefully investigated before attempting tree ring studies (Stahle et al., 1999; Worbes, 2002). Nevertheless, some researchers have attempted dendrochronological studies in Southern Africa, some with great success (e.g. Bhugeloo, 2014; Jones et al., 2009; Steenkamp et al., 2008; February et al., 2006; Fichtler et al., 2004; Stahle et al., 1999; February & Stock, 1998; Gourlay, 1995a). Hardwoods of several plant species offer some possibilities for dendrochronological

studies in Southern Africa, these include (but not limited to) *Brachystegia spiciformis*, *Senegalia burkei*, *Senegalia caffra*, *Vachelia erioloba*, *Senegalia hereroensis*, *Vachelia karroo*, *Senegalia nigrescens*, *Senegalia polyacantha*, *Vachellia robusta*, *Adonsonia digitata*, *Vachellia nilotica*, *Terminalia sericea*, *Dichrostachys cinerea*, *Senegalia mellifera*, *Widdringtonia cedarbergensis*, *Pterocarpus angolensis*, *Burkea africana and Pterocarpus angolensis (*Bhugeloo, 2014; Fichtler et al., 2004; Worbes, 2002; February & Stocks, 1998; Gourlay, 1995a).

Garcia-Suarez et al. (2009) reported that although tree-rings of tropical trees can provide continuous yearly paleo-climate records for regions or periods of time with no instrumental climate data, different species respond differently to climate parameters, some are more sensitive to moisture while others are temperature sensitive. Until now, very few studies have been done on tree rings as climate change indicators to contribute to the understanding of climate change in the Southern Hemisphere, in particular, Namibia.

CHAPTER 3: MATERIALS AND METHODS

3.1 Research design

A quantitative study was carried out at three research sites which are situated along a rainfall gradient in order to find out how rainfall patterns are reflected in tree rings of two encroacher species. The sites were (Figure 3.1):

1. John Alphons Pandeni Research Station (600 mm).
2. Farm Onyoka (450 mm).
3. Farm Ebenhaezer (250 mm).

These sites were selected on the basis that both *Dichrostachys cinerea* and *Senegalia mellifera* were present and were able to provide comparisons of their climatic signals. These sites are situated along a rainfall gradient and are sensitive to ENSO events (Steenkamp et al., 2008; Fichtler et al., 2004; Gourlay, 1995a) such that if that signal is strong enough, it must be able to be picked up by the two species. The geological features of the three sites are different (see Section 3.4 below). All these sites fall in regions where rainfall is a limiting factor on tree growth.

3.2 Tree species used for this study

This study focused on the two invader woody plant species, namely *Dichrostachys cinerea* and *Senegalia mellifera.* Midgley et al. (2005) reported that in Namibia, it is clear that the climate is changing to the advantage of *S. mellifera* and *D. cinerea* by extending their distribution range and they continue to colonize new areas as invasive species. According to Büntgen et al. (2007) such species can serve as climate change proxies. These species were selected on the basis that they are expanding their native

range in the present changing climate (Hauze & Tran, 2015; Joubert, Zimmermann & Graz, 2009). The two species show the most significant variations in density from north to south (de Klerk, 2004) where *D. cinerea* becomes less and less prevalent as one moves towards the south (less rainfall); whereas *S. mellifera* is more or less equally abundant at all the three sites.

Dichrostachys cinerea (commonly known as sickle bush) is a thorny woody species that reaches a height of 3 to 7 meters (Hauze & Tran, 2015). It has an open round crown up to 3 meters wide and has a deep tap root and many lateral horizontal roots that make it difficult to get rid of. *Dichrostachys cinerea* is found in frost-free areas, fallows and degraded lands (Hauze & Tran, 2015; Food Agriculture Organisation (FAO), 2011). It can be found in regions with 200 to 900 mm annual rainfall and it is thought to be drought resistance (FAO, 2011). Older trees produce seeds every year which survive for a long time in the soil and they bear fruits at young life stage (Joubert, Zimmermann & Graz, 2009). It also grows on different soil types, including clayey soils. The roots of *D. cinerea,* in association with nitrogen fixing bacterial, fix atmospheric nitrogen and the leaves can be used as green manure (FAO, 2011).

Senegalia mellifera (commonly known as black thorn) is a drought resistant woody species, which is wide-spread in arid and semi-arid areas in Africa. It grows better in sandy, clayey and stony-rocky soil (Hauze & Tran, 2015). The black thorn can be found in regions with 400-800 mm annual rainfall, however it can also grow in areas with 100 mm minimum annual rainfall (Hauze & Tran, 2015). It has an extensive root system that explores large volumes of soil, allowing it to survive in dry areas. It occurs either as a multi-trunked tree, which grows up to seven meters tall, with funnel shaped crown or as a single trunked tree that can reach a height of up to nine meters

(Hauze & Tran, 2015). In some areas it is considered as an invasive species as it can expand into and cover large areas and can form impenetrable thickets (Hauze & Tran, 2015). Unlike *D. cinerea*, *S. mellifera* seeds live shorter and last for only one season (Joubert, Rust, Smit, & Hoffman, 2017; Joubert, Zimmermann & Graz, 2009). Mass production of *S. mellifera* seeds, germination of seeds and establishment and survival of seedlings are promoted mostly by high rainfall (Joubert, Zimmermann & Graz, 2009; Kraaij, & Ward, 2006). *Senegalia mellifera* produces more pods with viable seeds when there is more soil water available to their roots (Joubert, Zimmermann & Graz, 2009). It appears that *S. mellifera* does not tolerate excessively cold or warm humid conditions since it does not occur naturally in these climatic areas (de Klerk, 2004; Donaldson, 1969). The roots *of S. mellifera* in association with nitrogen fixing bacterial fix atmospheric nitrogen (Joubert, Rust, Smit, & Hoffman, 2017; Kambatuku, 2010).

3.3 The invasive nature and significance of the two species

In Namibia, the abundance of the two species along a rainfall gradient is uneven (Joubert et al., 2014; de Klerk, 2004). Between the two species, *D. cinerea* is more abundant in a rainfall gradient ranging from 450 to ≥600 mm, from central-north to the north and north-east of Namibia while *S. mellifera* is more abundant in rainfall gradient ranging from 200 - 450 mm, from central-south to the south of Namibia (de Klerk, 2004). However, *S. mellifera* is the most widely distributed encroacher species, with *D. cinerea* in a strong second place (Joubert et al., 2014; de Klerk, 2004). Both

D. cinerea and *S. mellifera* are believed to be indicators of overgrazing in low rainfall areas (Hauze & Tran, 2015; Nonyane, 2013).

Dichrostachys cinerea is a native species to Namibia (O'Connor, Puttick & Hoffman, 2014; Orwa et al., 2009). It is a fast-growing species that has become an undesirable weed and is particularly a problem in areas where there has been overgrazing, trampled ground and on old lands where the grass cover has been removed (Chepape et al., 2011). In the areas where it invades; the tree forms very dense thickets making areas impenetrable (Chepape et al., 2011). Besides that, *D. cinerea* has many important uses. It has high potential for ravine afforestation and other conservation purposes on sites with poor soils (Chepape et al., 2011). It is also widely used for sand dune stabilization and soil conservation (e.g. in India). *Dichrostachys cinerea* is recommended for shallow soils, arid western and sub-humid alluvial plains and highly degraded calcareous wastelands in South Africa (Chepape et al., 2011). Leaves and fruits of *D. cinerea* are palatable to many animals such as cattle, giraffe, buffalo, kudu and impala (Jamala et al., 2013).

Although *S. mellifera* is a native species to Namibia, it is considered one of the most aggressive species (FAO, 2014; Orwa et al., 2009; de Klerk, 2004) because this species can form dense impenetrable thickets. It may outcompete grasses and other species in dry areas and become the only remaining species, causing a considerable reduction in seasonal grass yield leading to reduced rangeland productivity (FAO, 2017; Heuzé & Tran, 2015). Because *S. mellifera* has an aggressive root system, its use is limited on farms with crops (Heuzé & Tran, 2015; Orwa et al., 2009). However, when pruned regularly, *S. mellifera* provides animals with shade from the hot sun and it makes a good live fence and hedge in arid areas (Orwa et al., 2009). *Senegalia*

mellifera leaves and young shoots are nutritious and make fodder for livestock and wild animals (Nonyane, 2013). They are browsed by cattle, sheep, goats and wild animals such as black rhinos, kudus, elands and giraffes (Nonyane, 2013; Orwa et al., 2009).

3.4 Study area

The study was conducted at three research sites: John Alphorns Pandeni Research Station in the northern part of Namibia situated 20 km south of Grootfontein; Farm Onyoka on the Waterberg Plateau Park area in the central of Namibia, about 60 km east of Otjiwarongo; and Farm Ebenhaezer in the south-east, 120 km south-east of Windhoek and about 90 km south-west of Gobabis Town (Figure 3.1).

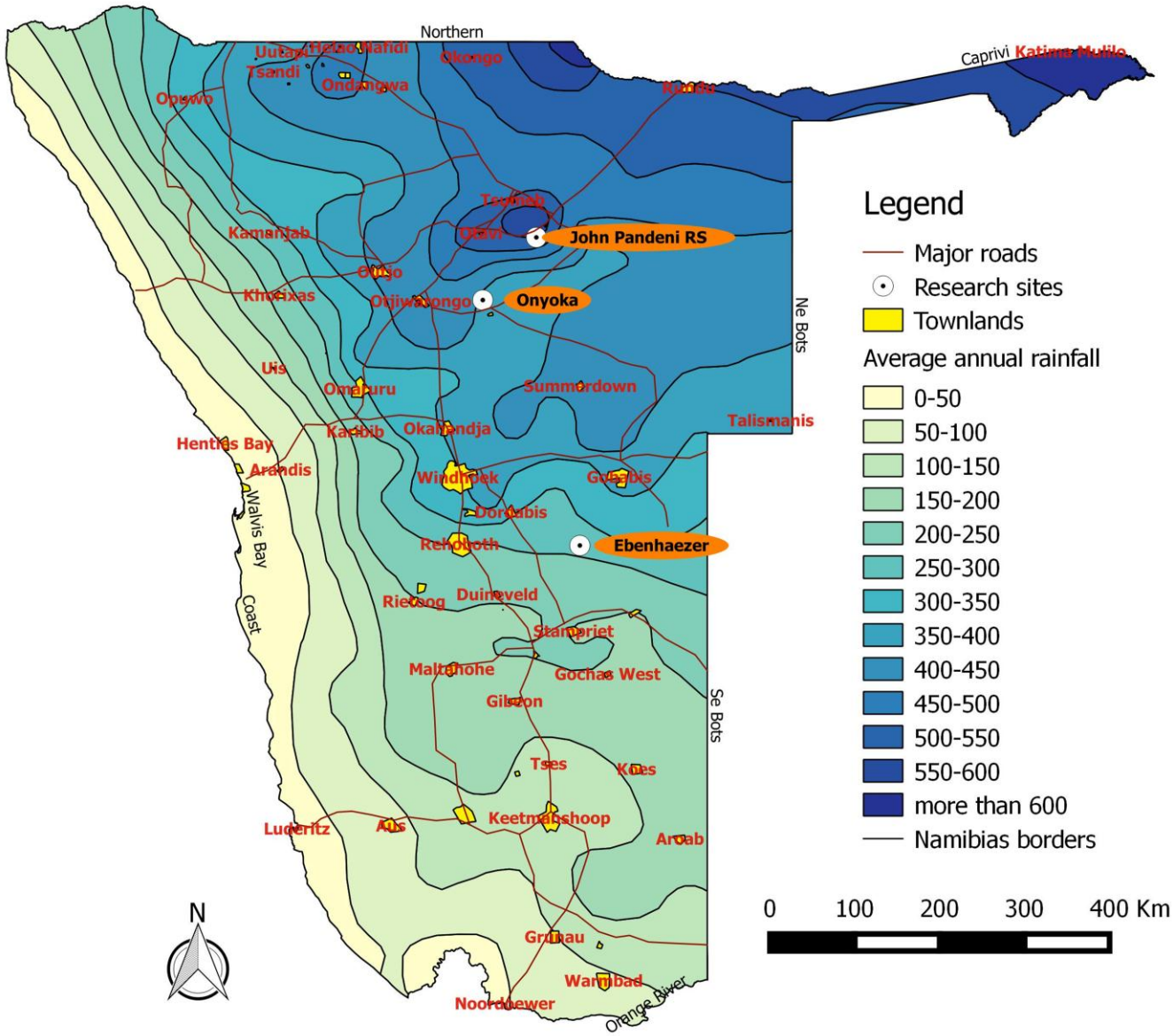


Figure 3.1: A map of Namibia showing the locations of the three research sites along a rainfall gradient (average annual rainfall data source at Ministry of Environment and Tourism (MET) (Mendelsohn et al., 2002)).

3.4.1 John Alphons Pandeni Research Station

3.4.1.1 Location and extent

John Alphons Pandeni Research Station is situated along the Tsumeb-Grootfontein Road (Trans-Caprivi Highway), 20 km southwest of Grootfontein (Figure 3.1 above) in the Otjozondjupa Region (S 19° 68´ 99" and E 17° 98´ 66"). The research station, which covers a total area of 6500 hectares (65 km²) (Nampa, 2011, p. 1), is a State land under the Ministry of Agriculture, Water and Forestry (MAWF).

3.4.1.2 Climate

John Pandeni Research Station is located in the wettest area of the region called "the maize triangle" due to orographic rainfall of the Tsumeb - Otavi - Grootfontein Mountains (Mendelsohn, Jarvis, Roberts & Robertson, 2002). This area receives an annual average rainfall of 550-600 mm (MET, 2013). The area receives summer rainfall starting from November in a form of showers and thunder storms (Mendelsohn et al., 2002). High rainfall usually occurs from January to March. Winter is the driest season which starts from May to August with July being the coldest month. According to Mendelsohn et al. (2002) average maximum temperature in this area ranges from 32 - 34°C in summer and the average minimum temperature ranges from 4 - 6°C in the winter. In the dry season humidity in this region ranges from 10 - 20% and in wet season it ranges from 80 - 90% (Mendelsohn et al., 2002).

3.4.1.3 Geology, soil and physical features

The station is situated in the mountainous area of the Grootfontein Metamorphic Complex and the Otavi group (Mendelsohn et al., 2002). It is found on the range of 1600 - 2000 metres above sea level (Mendelsohn et al., 2002). Most of the areas in this zone consist of limestone and dolomite rocks (Mendelsohn et al., 2002). The dominant soil type is mollic laptosols, generally known as cambisols. This soil type formed recently in geological time from medium and fine parental materials, which were deposited during sporadic flooding (Mendelsohn et al., 2002). Moreover, mollic leptosols are a soil type with good surface structure (Mendelsohn et al., 2002). This soil type has a medium level of fertility because of its good water holding capacity and internal drainage (Mendelsohn et al., 2002).

3.4.1.4 Flora and Fauna

The research station is found in the vegetation type of *Senegalia-Vachellia* tree and shrub Savanna biome, a sub biome called Karstveld (Mendelsohn et al., 2002). This type of vegetation biome covers Grootfontein-Tsumeb-Otavi Mountains and extends to Outjo and Okaukuejo in Etosha National Park (Mendelsohn et al., 2002). Karstveld consists of mixed woodlands, shrubs and grasses.

The most common woody plant species of this area includes *Terminalia prunioides, Burkea africana, Terminalia sericea, Senegalia mellifera, Colophospermum mopane* some *Vachellia* species and the most problem species of this area, *Dichrostachys cinerea* (Mendelsohn et al., 2002). There are also important grass species in this area

of which most are palatable to both livestock and wild animals. These include *Schimidtia kalahariensis, Stipagrotis uniplumis, Anthephora pubescens* and *Eragrostis trichophora* (Mendelsohn et al., 2002). Maize and sorghum are grown within the station for research, human consumption and for animal fodder (Nampa, 2011, p. 1).

Besides plants, there are numerous species of large and small animals and birds associated with them. The station has indigenous goats of four different breeds namely the Caprivi breed, Kavango breed, north-central or Ovambo breed and the Kunene or Kaoko breed (Nampa, 2011, p. 1). The station is also a home to well-adapted, Brahman, Simmentaler and Braunvieh cattle which are used for milk production. Other large animals include Kudu (*Tragelaphus strepsiceros*), vervet monkeys (*Cercopithecus pygerythrus*), Chacma baboon (*Papio ursinus*), Burchell's Zebra (*Equus burchellii*), Springbok (*Antidorcas marsupialis*), Red hartebeest (*Alcelaphus buselaphus*), Oryx (*Oryx gazella*), and Warthog (*Phacochoerus africanus*), Hayena (*Hyaena brunnea*). Species of birds include larger birds such as lesser spotted eagles (*Aquila pomarina*) and Lappetfaced Vulture (*Torgos tracheliotus*). There are more than 60 species of reptiles and more than 12 species of amphibians (Mendelsohn et al., 2002).

3.4.2 Onyoka

3.4.2.1 Location and extent

Farm Onyoka is a Government farm under the Ministry of Agriculture, Water and Forestry. It is situated about 60 km east of Otjiwarongo and about 5km north of Okakarara Town in Otjozondjupa Region (Figure 3.1 above). The farm which covers a total area of about 3500 hectares (35 km²) (C. Kamburona[1], personal communication), is located between S 20°42′71" and E 017°35′57" (Mendelsohn et al., 2002, Mukaru, 2009). It is found on the southern side of the Waterberg Plateau Park (WPP, a characteristic Table Mountain that covers an area of approximately 4100 km² of uplifted sandstone).

3.4.2.2 Climate

The average annual rainfall of Okakarara (close to Onyoka Site) ranges from 350-400 mm (MET, 2013; Mendelsohn et al., 2002). The area receives a summer rainfall starting from November to March and winter months are the driest, starting from May to August (Mendelsohn et al., 2002). Average maximum temperature during the hottest summer month, November to February ranges from 32 to 34°C.

[1]C. Kamburona is a lecturer from the University of Namibia, Ogongo campus who was part of the OPTIMASS project who did a research on farm Onyoka.

The average minimum temperature ranges from 4 - 6°C in the winter months (Mendelsohn et al., 2002). Relative humidity in the dry season ranges from 10 - 20% and ranges from 70 - 80% in the wet season (Mendelsohn et al., 2002).

3.4.2.3 Geology, soil and physical features

Farm Onyoka is found on the range of 1400 - 1600 metres above sea level (Mendelsohn et al., 2002). The farm and the surrounding area consist of nutrient-poor Arenosols, which are derived from leached out red quartzite sand (Mukaru, 2009; Mendelsohn et al., 2002). The most dominant soil type of the farm and the surrounding area is red sandy soil, which was derived from the eroded nearby uplifted Table Mountain of red sandstone (Ndunge, 2018).

3.4.2.4 Flora and fauna

Farm Onyoka is found in a mixed biome of *Senegalia-Vachellia* trees and broadleaved trees and shrub Savanna (Mendelsohn et al., 2002). This biome is dominated by several tall tree species that form a moderate thick canopy in some places (Mendelsohn et al., 2002). The vegetation on the farm consists of more than 400 species of plants (Mukaru, 2009). Common woody species include *Terminalia sericea, Burkea africana, Combretum collinum, Ochna pulchra, Dichrostachys cinerea, Grewia flavescens, Grewia retinervis, Senegalia mellifera, Ochna pulchra, Peltophorum africanum* and *Ziziphus mucronata*. Common grass species include *Stipagrostis uniplumis*, *Andropogon schirensis*, *Digitaria seriata*, *Eragrostis pallens*,

Eragrostis rigidior, *Eragrostis jeffreysii* and *Panicum kalaharense* (Erb, 1993, cited in Mukaru, 2009).

Onyoka is a mixed farm of livestock and game animals. Livestock include cattle, sheep and goats. Wild herbivores includes, Roan antelope (*Hippotragus equinus*), Sable antelope (*Hippotragus niger*), tsessebe (*Damaliscus lunatus lunatus*), Giraffe (*Giraffa camelopardalis*), Eland (*Taurotragus oryx*), Oryx (*Oryx gazella*), Kudu (*Tragelaphus strepsiceros*), Red hartebeest (*Alcelaphus buselaphus*), Klipspringer (*Oreotragus oreotragus*), Duiker (*Sylvicapra grimmia*), Steenbok (*Rhaphicerus campestris*) and Warthog (*Phacochoerus africanus*) (Mukaru, 2009). Other animals are also found within the farm including small mammals, reptiles, amphibians and numerous species of birds.

3.4.3 Ebenhaezer

3.4.3.1 Location and extent

Farm Ebenhaezer is a private commercial farm of mixed livestock in Omaheke Region. The farm is situated in the south-east, about 160 km from Windhoek and south-west of Gobabis (Figure 3.1 above). The farm which covers a total area of 2200 hectares (22 km²) (Rodgers, Bilton & Hauptfleisch, 2017) is located between S23°12´57" and E18°27´22", and in the range between 1400 – 1600 meters above sea level (Mendelsohn et al., 2002).

3.4.3.2 Climate

Farm Ebenhaezer is characterized as semi-arid to arid as it receives average annual rainfall ranging from 200 mm to 350 mm and it is unreliable and irregular, and average evaporation rate ranges from 2000 - 2500 mm annually (Rodgers, Bilton & Hauptfleisch, 2017; Mendelsohn et al., 2002). The highest rainfall occurs in summer, starting from November to April. The dry period lasts for five to seven months and the growing season starts a little earlier from October/November until April. Average maximum temperature ranges from 32 - 34 °C in the summer months and the average minimum temperature range from 2 - 4 °C in the winter months. In the winter months relative humidity ranges from 10 - 20% and ranges from 70 - 80% in the rain months (Mendelsohn et al., 2002).

3.4.3.3 Geology, soil and physical features

Ebenhaezer is in a flat area with some sand dunes of the Kalahari Soil Group, and the geological time formation of this soil type is 70 million years ago (Mendelsohn et al., 2002). The most dominant soil types of this area are arenosols which consist of more than 70 percent wind-blown sand (Rodgers, Bilton & Hauptfleisch, 2017; Mendelsohn et al., 2002). The soil is poor in nutrients because water infiltration is rapid and nutrients are leached out of the soil (Rodgers, Bilton & Hauptfleisch, 2017).

3.4.3.4 Flora and fauna

Farm Ebenhaezer is found in the area of southern Kalahari vegetation type in the broad-leaved trees and shrub savanna biomes (Rodgers, Bilton & Hauptfleisch, 2017). The vegetation of this area consists of dwarf shrub, vegetation dunes and thorn bush encroachment. The dominant woody plant species are *Senegalia mellifera*, *Boscia albitrunca, Vachellia erioloba, Vachellia karoo, Vachellia hebeclada, Grewia flava* and *Albizia anthelmintica*. *Dichrostachys cinerea* is present; however, its density is very low. The dominant grass genera are *Aristida* and *Stipagrostis* (Rodgers, Bilton & Hauptfleisch, 2017).

Ebenhaezer is a livestock farm of karakul sheep, cattle and horses. There are also small animals of which some are carnivores, which cross the fence from the neighbouring Kuzikus Farm such as, Springhare (*Pedetes capensis*), Black-footed cat (*Felis nigripes*), African wild cat (*Felis silvestris lybica*), Small-spotted genet (*Genetta genetta*), Bat-eared fox (*Otocyon megalotis*), Cape porcupine (*Hystrix africaeaustralis*) (Rodgers, Bilton & Hauptfleisch, 2017). There are also more than ten species of scorpions, more than seven species of termites, close to seventy species of reptiles and more than one hundred and twenty species of birds in the area around the farm (Mendelsohn et al., 2002).

3.5 Data collection

3.5.1 Field sampling and sample preparation

Tree disc samples of the two species were collected from John Alphons Pandeni Research Station and farm Onyoka in September 2015 and those of the same two species from Ebenhaezer were collected in September 2016. From each research site, twenty four individual trees of *D. cinerea* of different stem circumferences of unknown age were cut. Also from each site twenty four individual trees of *S. mellifera* of different stem circumferences of unknown age were cut. The selected sample stems ranged from 3 cm to 15 cm in diameter, taken between 0.7 m and 1.0 m height from the main stem using a bow saw following the methodology of Williams (2010). Stem circumferences were measured around the cutting zone using a tape measure. Tree heights were measured using a 2.5 m range pole. For taller trees, heights were estimated to the nearest half meter. All individual trees that were cut were selected randomly from a population of at least three hundred individuals, except the *D. cinerea* specimens from Farm Ebenhaezer as the abundance of this species in the south is very low. Therefore, *D. cinerea* trees from Ebenhaezer were selected from a population of less than 300 individuals.

Two stem discs were sliced from each tree. Stem diameters were measured with a transparent ruler and all the measurements were recorded. All forty eight specimen discs of each tree species per site were allowed to dry and pre-polishing (using a file and a coarser sand paper of grain size 40) was done manually in the Biological Science Laboratory of the University of Namibia. After pre-polishing, all the discs were transported to Alfred Wegener Institute (AWI) of the University of Potsdam,

Germany where all the discs were then polished again. First, a little bit of water was applied to the stem wooden surface to get it wet for easy polishing. After some minutes (20 to 40 minutes), sand papers were used to smoothen the discs wooden surface, starting with a coarser grain size 60 phi and working to the finest grain size 1200 phi until the rings were clearly visible under the binocular microscope; and this was done manually.

Stem and xylem diameters were measured after the discs were polished. A transparent thirty centimeter (30 cm) ruler was used to measure the average diameter (cm) of the stem discs for all specimens of each species. Each stem diameter was measured five times at different points of the stem (excluding the bark) across the heart wood, and then the total diameters were divided by five to get the average stem diameter (cm). To find the average heart wood diameters (cm), the zone that separates the heart wood from sap wood was clearly marked at several points with a HB pencil under a binocular microscope. Thereafter, five heart wood diameter measurements were taken using a transparent thirty centimeter (30 cm) ruler, and then the totals were calculated and divided by five to get the average heart wood diameter of each specimen. The discs were then scanned, so that a digital image of the discs was obtained. The scanning methodology was done with a scale such that the disc size measurements could be associated with each scanned image measurements of the same disc. The disc scans were then taken to the WinDENDRO (Heinrich et al., 2009) software for processing. After processing in WinDENDRO, the information was taken to COFECHA software. The number of growth rings were obtained from the summary table of COFECHA result (see Section 3.5.2 below).

Out of all the forty eight discs from each site, only twenty four best discs (those whose heart wood was at, or closer to the center and without major damage such as insect damage) were chosen for analysis. The rest of the discs were kept as voucher specimens.

3.5.2 Sample analysis and ring width measurement

Specimens from each site were scanned in EPSON scanner to acquire their images. They were scanned at 2400x resolution and images were saved as tiff files. Out of the twenty four discs, only twelve best discs from twelve trees (those with heart woody at center and with clearly visible rings under the binocular microscope, and stem diameter that ranges from 3-15 cm) from each site were selected for analysis by the WinDENDRO software (Heinrich et al., 2009).

All twelve images from the twelve specimens of the two species from each site were loaded onto the software one at a time. A calibration file (a file of measurements in mm three decimal place), which correspond to the pixel size of the images. This file is prepared in the calibration section within the WinDENDRO software before loading any image. The calibration file was prepared according to the images resolution and was loaded onto the software together with the images. Before starting with any analysis, a calibration file was loaded into WinDENDRO, and then an image was loaded after. Whenever the ring/rings on the image was/were not clearly visible in the software or whenever one was not sure whether it was a ring or not, the specimen was viewed under the binocular microscope for ring confirmation.

All ring measurements were done in WinDENDRO software. To make sure that all the rings were correctly detected on each specimen's image, at least four paths were created from pith to bark. All tree ring measurement data were saved. Later all ring measurement data from WinDENDRO were filtered to numerical data from codes using TUCSON software. TUCSON is dendrochronological software that comes and works together with WinDENDRO software. Its purpose is to filter coded data from WinDENDRO to numerical data. Tree ring data from TUCSON were cross-dated and verified using the programme COFECHA (Perkins et al., 2018; Novak et al., 2013).

Cross-dating was done to determine if the ring widths of each tree were correlating to all other trees of the same species from the same site. COFECHA creates a master chronology of all the discs for one species from one site and calculates the correlation coefficient to indicate how well the interannual variability in the ring width correlates with the other ring-width series (Maxwell, Wixom & Hessl, 2011). Whenever the results from COFECHA table showed that a ring/rings was/were missed or extra ring/rings was/were added when a specimen's image was analyzed in WinDENDRO, the specimen's image was re-worked in WinDENDRO to either look for and add the missing ring/rings or to look for and remove the added ring/rings. This was repeated until the COFECHA result table showed that all the rings were identified correctly. However, if the missing ring or added ring was not found, it was ignored depending on the value of the master dating series of COFECHA results table. Once the value was ≥30 the ring was carefully looked for under WinDENDRO and added or removed. When the value was <30, it was ignored. This did not have any adverse effects on the results or the interpretation of the results.

3.5.4 Rainfall data

This study required annual rainfall data for relationship with ring width and for future climate modeling. Therefore, reliable meteorological data consisting of daily, monthly and annual rainfall records for at least eight decades were obtained from Meteorological Services of Namibia (MSN) for stations close to all three research sites where trees were sampled from. However, only daily rainfall records that were added up to get the annual rainfall data were used in this study. For farm Ebenhaezer, the nearby (< 20 km) annual rainfall data for Lut Willer Farm were used. Annual rainfall record for Otjiwarongo was used for Onyoka (< 60 km) site, and Grootfontein's annual rainfall data were usedfor John Alphorns Pandeni Research Station (≤ 20 km).

3.5.5 Data analysis

Tree ring numerical data from TUCSON software were the data used in this study. The final tree ring width measurements for linear relationship with annual rainfall from each site and for the median comparison between individuals of one species along a rainfall gradient were based on discs from four best trees, (those that best correlated to each other among the twelve individuals from the same site, correlation with master in COFECHA at least: $r \geq 0.5$) per species from each sites (Ingo Heinrich[2], personal communication).

[2] I. Heinrich is a dendrochronologist at the Helmholtz Centre Potsdam, GFZ - Research Centre for Geosciences, Climate Dynamics and Landscape Evolution, Telegrafenberg, 14473 Potsdam, Germany.

The rest were excluded due to weak and/or non-correlation (correlation with master in COFECHA: $r < 0.5$) to the other eleven specimens. For the relationship between ring numbers and stem diameter; and xylem diameter and stem diameters of all the twelve specimens of each species from each site were used, except *D. cinerea* from Ebenhaezer where only eight trees were used because these were the only available best specimens. Statistical analysis for all ring width, stem and xylem measurements were done in the Statistical Package for Social Science for windows (IBM SPSS) version 25 (Bhugeloo, 2014). All data were tested for normality to determine their nature of distribution using Shapiro Wilk test ($P > 0.05$). When data were not normally distributed, a non-parametric test was conducted. The Shapiro Wilk test, which is best for testing small sample size was used since the sample sizes for this study were less than 2000 (Dytham, 1999, cited in Shifa, 2017). The scale that were used to indicate the strength of R^2 were (as it is also recommended in dendrochronology): 0< to ≤0.2 very weak, 0.2> to ≤0.4 weak, 0.4< to ≤0.6 moderate, 0.6< to ≤0.8 strong and 0.8< very strong (Pomortseva, Pomortseva, Rhozhin, & Trotimtsev, 2019; Warne, 2011; Cleaveland & Stahle, 2004).

To determine whether rainfall gradient influenced the width of growth rings in *Dichrostachys cinerea* and *Senegalia mellifera*, a Simple Linear Regression test was performed (Bhugeloo, 2014; Heinrich, 2009).

To determine the relationship between the numbers of growth rings and the stem diameter of the two species along a rainfall gradient, a Simple Linear Regression analysis was performed. Similarly, to determine the relationship between xylem diameters and stem diameter of the two species along a rainfall gradient, a Simple

Linear Regression analysis was performed. To compare tree ring growth patterns in order to infer survival strategies of the two tree species along a rainfall gradient, a Kruskal Wallis test was performed (Steenkamp et al., 2008). To compare the median ring width between the two species per site, a Mann-Whitney U test was used. When differences between medians were found, a Bonferroni Correction test was conducted to identify where the significant differences were.

CHAPTER 4: RESULTS

4.1 The reflection of rainfall variations (rainfall gradient) in tree rings of *Dichrostachys cinerea* and *Senegalia mellifera* at different sites

4.1.1 The relationship between *Dichrostachys cinerea* ring width and annual rainfall

4.1.1.1 Ebenhaezer (250 mm per annum)

There was no significant linear relationship between ring width and rainfall ($y= 0.0021x+0.7697$, $R^2 = 0.085$; $P=0.132>0.05$). Rainfall explained only 8.5% of the variations in ring width. The ring width of *D. cinerea* show that high rainfall peak occurs after every five to seven years in the area of Ebenhaezer (Figure 4.1a). Overall, the same Figure shows that since 1989 until 2005, there had been an increase on the annual rainfall and so do *D. cinerea* ring width. The ring width was thinner (below 1.000 mm) in 2006 and 2007 but rainfall on the same Figure shows that during those two years rainfall was high. Excessive downpours of rainfall do not allow for seepage, rather they favour run-off and thus denying the tree much needed moisture. According to the ring width, from 2008 it rained well for five years and there was also an increase in *D. cinerea* ring width until it dropped down for three years from 2013 to 2016, even though annual rainfall bars indicates that rainfall was high from 2014 until 2016.

4.1.1.2 Onyoka (450 mm per annum)

There was no significant linear relationship between ring width and rainfall ($y= -0.0006x+1.6581$, $R^2 =0.084$, $P=0.119 >0.05$). Rainfall explained only 8.4% of the variations in ring width. Figure 4.1b show that whether rainfall in a specific year is high

or low, the ring width of *D. cinerea* from Onyoka is not affected. *Dichrostachys cinerea* from this site does not clearly show the frequency of high rainfall peak either (Figure 4.1b).

4.1.1.3 John Pandeni (600 mm per annum)

There was a weak significant linear relationship between ring width and rainfall ($y= 0.0012x+0.9008$, $R^2=0.247$, $P=0.022 <0.05$). Rainfall explained 24.7% of the variations in ring width. The ring width of *D. cinerea* from John Pandeni followed the rainfall pattern (Figure 4.1c), showing no much difference (nearly all above 1.000 mm ring width) from 1994 to 2014 when rainfall was high or low, except in 2002 and 2003 when rainfall was higher than 400 mm/a, but the ring width formed in these two years were below 1.000 mm. From the tree ring history, we can confidently infer that high rainfall peaks around John Pandeni Research Station occur after every three to four years.

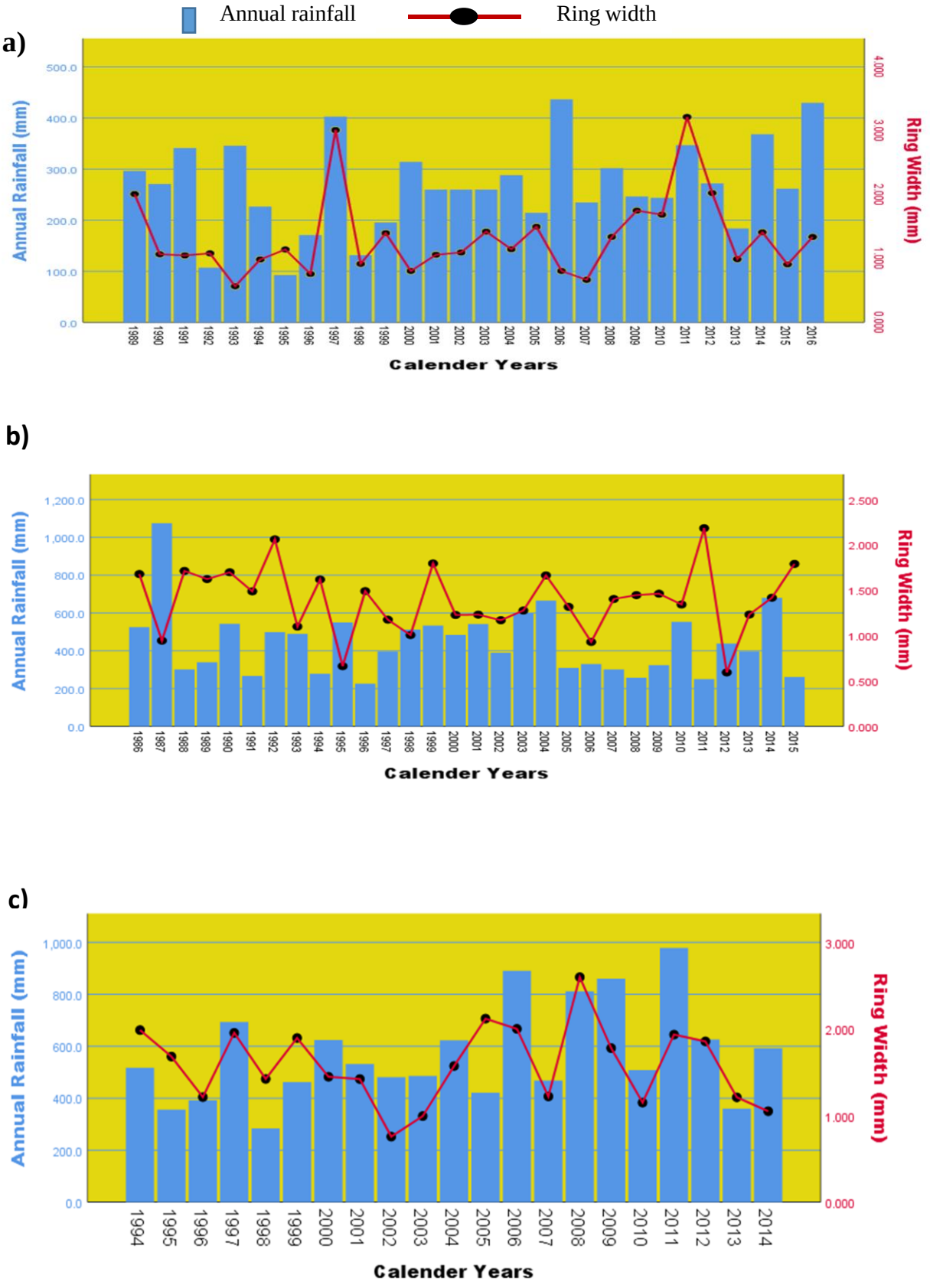


Figure 4.1: The relationship between *Dichrostachys cinerea* (4 trees) ring width (mm) and annual rainfall (mm) along a rainfall gradient (**a** - Ebenhaezer (250 mm); **b** - Onyoka (450 mm); and **c** - John Pandeni (600 mm)).

4.1.2 The relationship between *Senegalia mellifera* ring width and annual rainfall

4.1.2.1 Ebenhaezer (250 mm per annum)

There was no significant linear relationship between ranfall and ring width (y= -0.0006x+1.6505, R^2=0.018, P=0.477 >0.05). Rainfall explained only 1.8% of the variations in ring width. The ring widths of *S. mellifera* were not affected by the amounts of rainfall on this site. *S. mellifera* formed wider rings from 1992, 1994 to 1996 and from 2000 to 2003 but rainfall was low these years. In 1988, 1997 and 2016 it rained well, however *S. mellifera* from this site formed narrow rings (Figure 4.2a).

4.1.2.2 Onyoka (450 mm per annum)

There was no significant linear relationship between ranfall and ring width (y= 0.0002x+1.254, R^2=0.011, P=0.521 >0.05). Rainfall explained only 1.1% of the variations in ring width. The ring width of *Senegalia mellifera* on this site show that high rainfall peak occurs every after four to five years (Figure 4.2b). The same Figure shows that the rings formed from 1976 to 1980, 1996 to 1999 and from 2006 to 2011. *S. mellifera* were thick, but rainfalls in those same years were low.

4.1.2.3 John Pandeni (600 mm)

There was no significant linear relationship between ranfall and ring width (y= 0.0013x+1.1004, R^2=0.110, P=0.092 >0.05). Rainfall explained 11.0% of the variations in ring width. *Senegalia mellifera* ring widths were smaller compared to the rest of the years from 1999 to 2003 (Figure 4.2c) regardless of high rainfall during

same years (>450mm/a). According to the ring width of *S. mellifera* and annual rainfall data on the same Figure, annual rainfall quantity received on this site had increased since 1988, from < 400 mm/a in 1988 to >600 mm/a in 2013 and interestingly, *S. mellifera* ring width followed rainfall patterns from 2002 to 2009 by forming wider rings when rainfall was high and narrower rings when rainfall was low. Additionally, *S. mellifera* ring width shows that high rainfall peak on this site occurs every after three to four years (Figure 4.2c).

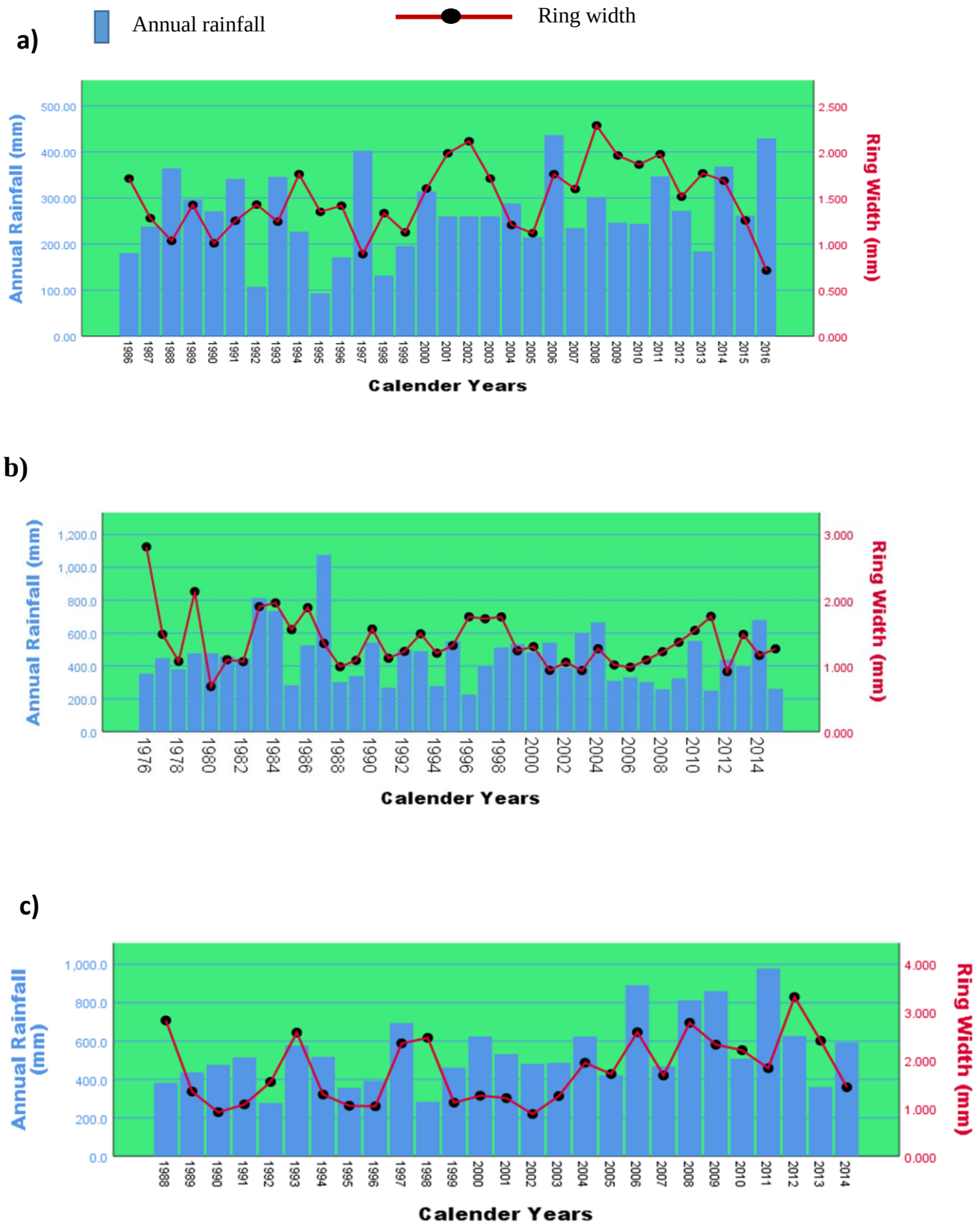


Figure 4.2: The relationship between *Senegalia mellifera* (4 trees) ring width (mm) and annual rainfall (mm) along a rainfall gradient (**a** - Ebenhaezer (250 mm); **b** - Onyoka (450 mm); and **c** - John Pandeni (600 mm)).

4.1.3 Comparison of site-specific median ring width between *Dichrostachys cinerea* and *Senegalia mellifera*

4.1.3.1 Ebenhaezer (250 mm per annum)

A Mann-Whitney U test indicates that there was a significant difference in the median ring width between *D. cinerea* and *S. mellifera* from Ebenhaezer (U = 284.500, P = 0.023< 0.05, Z = -2.269). Every year, *S. mellifera* adds more amount of woody material compared to *D. cinerea* for their secondary growth (Figure 4.3).

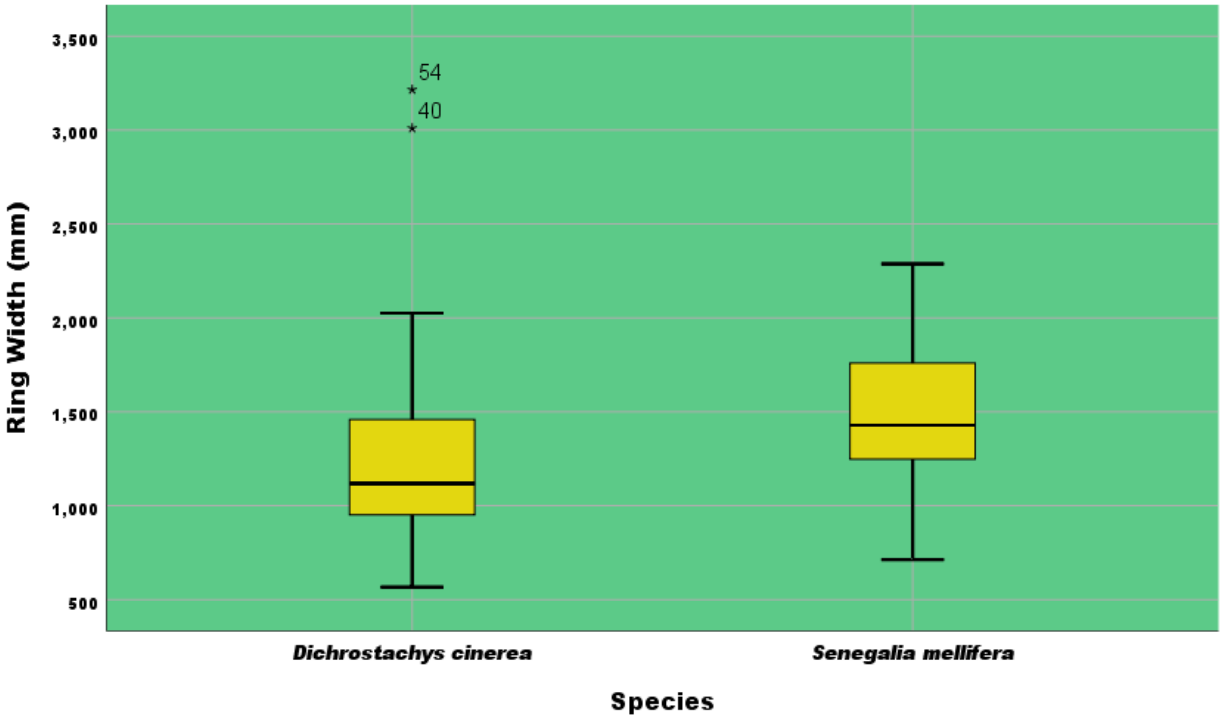


Figure 4.3: Comparison of the median ring width between *Dichrostachys cinerea* and *Senegalia mellifera* from Ebenhaezer.

4.1.3.2 Onyoka (450 mm per annum)

There was no significant difference in the median ring width between *D. cinerea* and *S. mellifera* from Onyoka (U = 532. 500, P=0.423 > 0.05, Z = - 0,801). Every year, both of the two species at this site add more or less the same amount of woody material for their secondary growth (Figure 4.4).

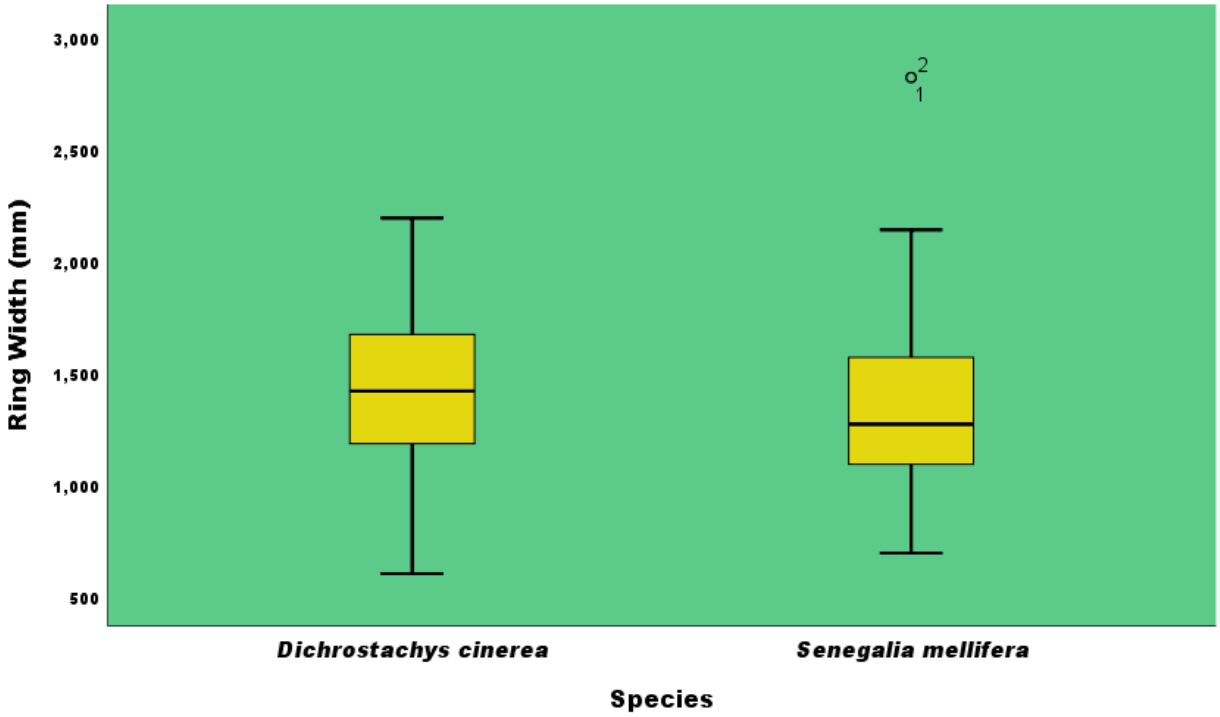


Figure 4.4: Comparison of the median ring width between *Dichrostachys cinerea* and *Senegalia mellifera* from Onyoka.

4.1.3.3 John Pandeni (600 mm per annum)

Mann-Whitney test indicates that there was no significant difference in the median ring width between *D. cinerea* and *S. mellifera* from John Pandeni (U = 265.000, P = 0.401> 0.05, Z = - 0,840). Both species at this site add more or less the same amount of woody material for their secondary growth (Figure 4.5).

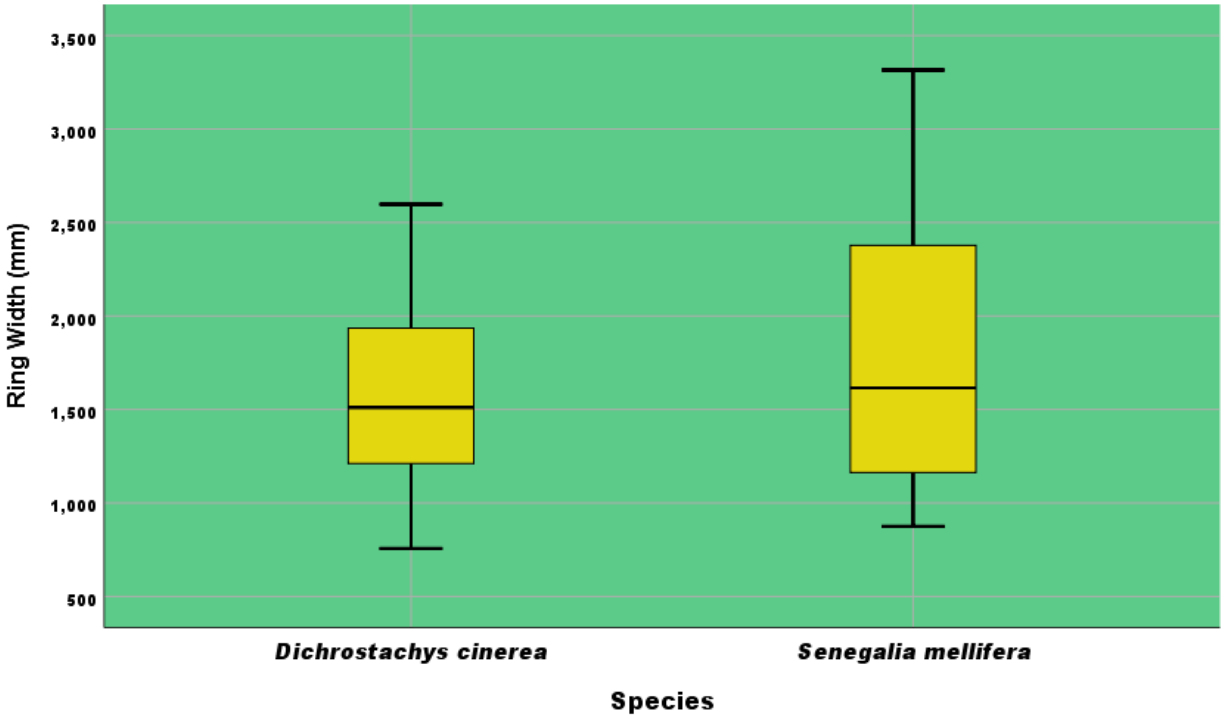


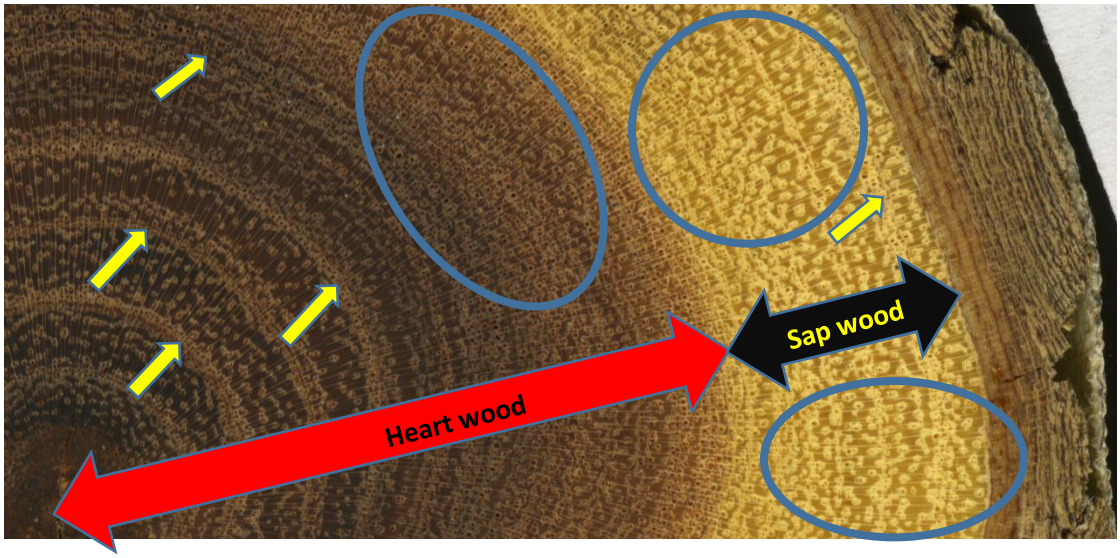
Figure 4.5: Comparison of the median ring width between *Dichrostachys cinerea* and *Senegalia mellifera* from John Pandeni.

4.2 The formation and characteristics of distinctive growth rings in *D. cinerea* and *S. mellifera*.

The yellow arrows on Figure 4.6a indicate the position of the growth ring boundaries and direction of growth, from pith to bark in *D. cinerea*. The red arrow on the same figure indicates the zone of the heartwood from pith and the black arrow indicates the zone of the sap wood. The blue circles show the vessel density on the centre and margin of the growth ring zone in *D. cinerea*. The rings are dense on the ring margin than on the ring centre on *D. cinerea*. Heartwood diameter in *D. cinerea* occupies a larger area in relation to the stem circumference compared to the sap wood (Figure 4.6a).

The yellow arrows on Figure 4.6b indicate the position of the growth ring boundaries and direction of growth, from pith to bark in *S. mellifera*. The red arrow indicates the zone of the heartwood from pith and occupies a smaller area in relation to the stem circumference. The black arrow indicates the zone of the sap wood and occupies a larger area in relation to stem circumference compared to the heartwood. The blue circles show the vessel density on the centre and margin of the growth ring zone in *S. mellifera* and contain large vessels and less dense throughout in most rings (Figure 4.6a). Heartwood diameter in *S. mellifera* occupies a smaller area in relation to the stem circumference compared to the sap wood (Figure 4.6b).

a)



b)

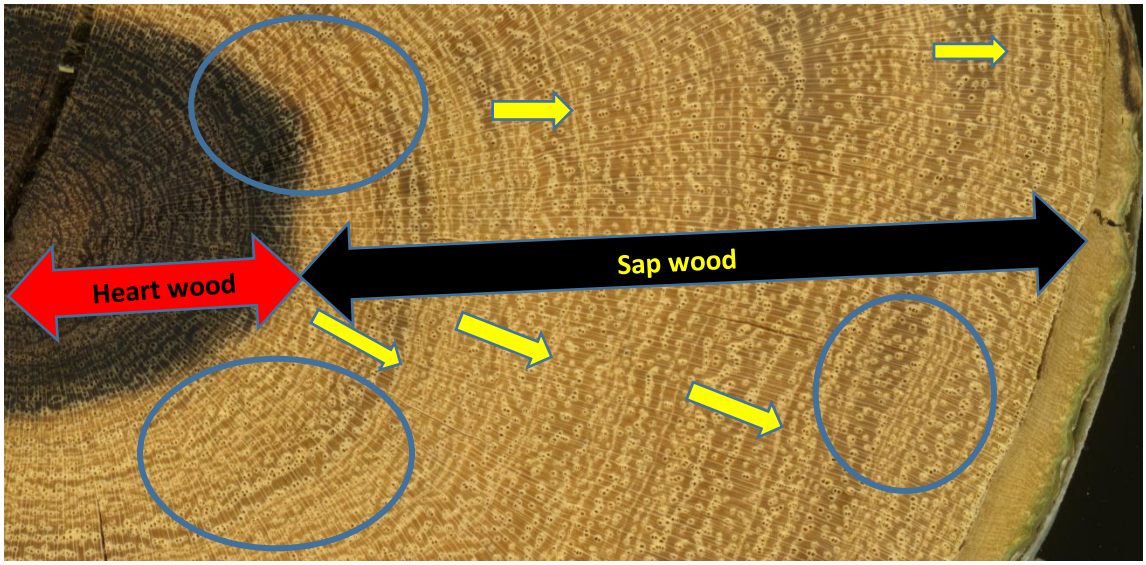


Figure 4.6: Stem discs showing the growth rings of *Dichrostachys cinerea* (4.6a) and *Senegalia mellifera* (4.6b). See section 4.2 above for the interpretation of the coloured arrows and circles.

4.3 Comparison of wood anatomy and ring morphology of *Dichrostachys cinerea* stem discs along a rainfall gradient

4.3.1 Wood anatomy and ring morphology of *Dichrostachys cinerea* stem discs

4.3.1.1 Ebenhaezer (250 mm per annum)

Vessels of *D. cinerea* from Ebenhaezer are very small and dense (clumped) (blue circle) (Figure 4.7a). The spot in the green circle on the same Figure was a scar from insect damage recorded in the rings. The rings are thin and dense. Rings that form in *D. cinerea* are irregular due to wet and dry seasons and the rings that form during dry years are very small with tiny and clumpy vessels. The entire stem is almost covered in dark colour of the heartwood. A linear regression test indicates that there was a very strong positive linear relationship between *D. cinerea* stem diameter and xylem diameter ($y = 1.33+1.05x$, $R^2= 0.976$, $P= 0.000< 0.05$). Stem diameter explained 97.6% of xylem diameter. The larger the stem size of *D. cinerea* from this site, the larger the heartwood diameter (Figure 4.8a).

4.3.1.2 Onyoka (450 mm per annum)

The vessel sizes of *D. cinerea* from this site are a little larger and are not as clumpy as the ones from Ebenhaezer. Only the vessels in the orange circle which are smaller and clumpy (Figure 4.7b). Although the dark brown colour of the heartwood occupied a larger area, the light brown colour of the sap wood in *D. cinerea* from this site is larger compared to the one on the drier site (Figure 4.7b). A linear regression test indicates that there was a moderate positive linear relationship between *D. cinerea* stem diameter and xylem diameter from Ebenhaezer ($y = 0.51+0.56x$, $R^2= 0.572$, P=

0.004< 0.05). Stem diameter explained 57.2% of xylem diameter. Although the xylem diameter of *D. cinerea* increase as the stem size increase, the stem size does not necessarily predict the size of the xylem diameter (Figure 4.8b).

4.3.1.3 John Pandeni (600 mm per annum)

The ring width of *D. cinerea* from this site are wider and clear. Vessel sizes are larger and scattered, except the ones in the green circle where the vessels are smaller and clumpy (Figure 4.7c). A linear regression test indicates that there was a very strong linear relationship between *D. cinerea* stem size and xylem diameter from John Pandeni ($y = 0.18+0.81x$, $R^2= 0.911$, $P= 0.000< 0.05$). Stem diameter explained 91.1% of xylem diameter. The Heartwood diameter is strongly predicted by the stem size (Figure 4.8c).

a)

b)

c)

Figure 4.7: Stem discs of *Dichrostachys cinerea* compared along a rainfall gradient (**a** - Ebenhaezer (250 mm); **b** - Onyoka (450 mm); **c** - John Pandeni (600 mm). See section 4.2 above for the interpretation of the coloured arrows and circles.

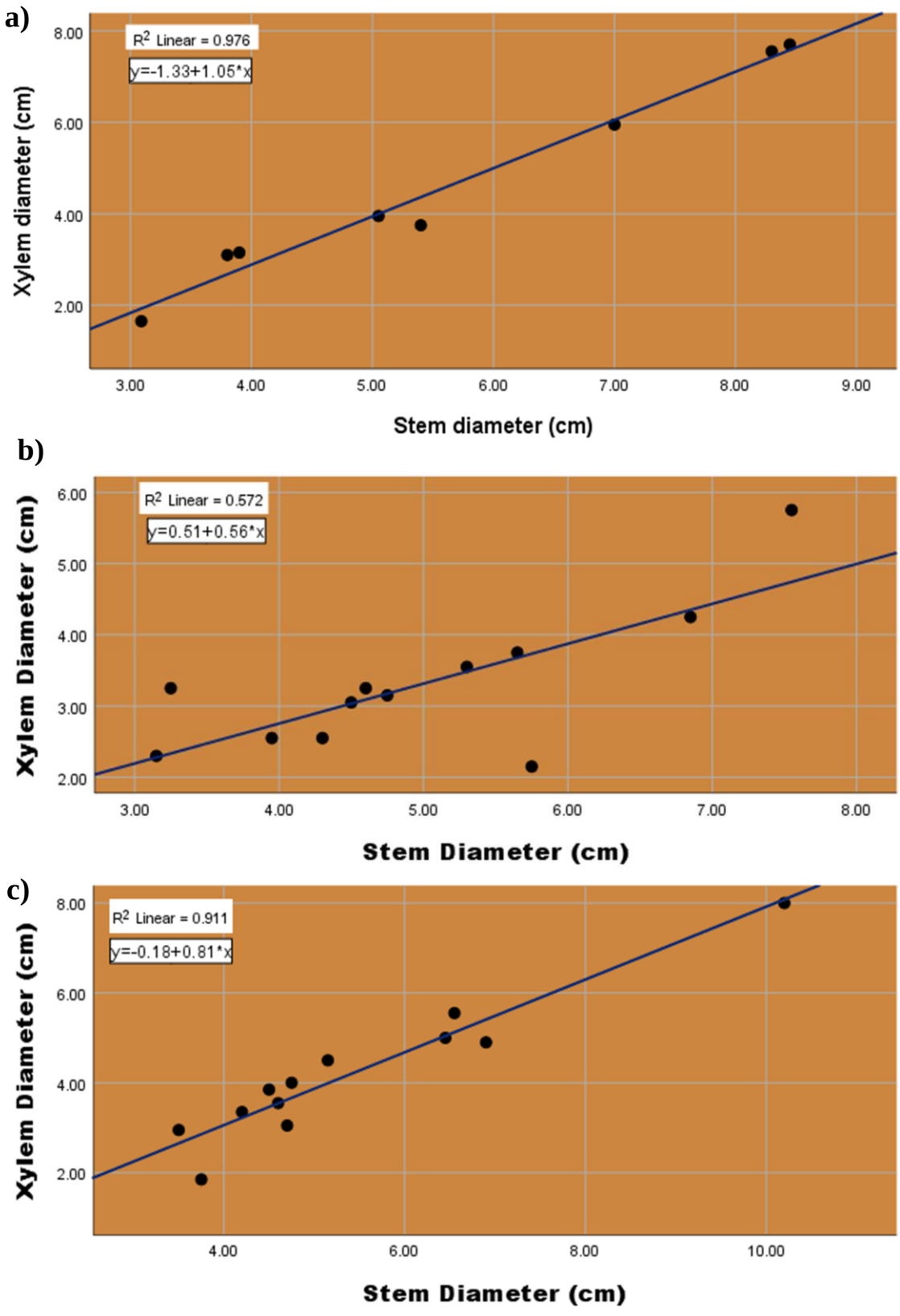


Figure 4.8: Relationship between *Dichrostachys cinerea* stem diameter (cm) and xylem diameter (cm) along a rainfall gradient (**a** - Ebenhaezer (250 mm); **b** - Onyoka (450 mm); **c** - John Pandeni (600 mm)).

4.3.2 Wood anatomy and ring morphology of *Senegalia mellifera* stem discs along a rainfall gradient

4.3.2.1 Ebenhaezer (250 mm per annum)

Vessels in *S. mellifera* from Ebenhaezer are larger and scattered. *Senegalia mellifera* from this site clearly show the two types of cells, dark and light colours, in the red circles (Figure 4.9a) that form at the beginning of spring and late summer. The yellow arrows in the red circles show that rings that form in *S. mellifera* from this site are larger and clear and nearly regular. The same figure also shows that the large area of the stem is covered by sapwood. A linear regression test indicates that there was a moderate positive linear relationship between *S. mellifera* stem diameter and xylem diameter ($y = 2.65+0.78x$, $R^2= 0.586$, $P= 0.004<0.05$). Stem diameter explained 58.6% of xylem diameter. Even though the increase of stem size results in the increase of xylem diameter, the size of *S. mellifera* stem from Ebenhaezer does not necessarily tell how large the xylem diameter is (Figure 4.10a).

4.3.2.2 Onyoka (450 mm per annum)

The vessel sizes and density on the growth ring centre and margin (in the red circle) are very small and clumpy (Figure 4.9b). A linear regression test indicates that there was a very strong linear relationship between stem diameter and xylem diameter in *S. mellifera* from Onyoka ($y = 2.06+0.73x$, $R^2= 0.946$, $P= 0.000< 0.05$). Stem diameter explained 94.6% of xylem diameter. The xylem diameter of *S. mellifera* increase as the stem diameter increases (Figure 4.10b).

4.3.2.3 John Pandeni (600 mm per annum)

The yellow arrows in Figure 4.9c shows that the ring width of *S. mellifera* from John Pandeni are wider and clear. The vessel sizes are larger and scattered. However, the vessels on the ring margins are a little smaller and clumpy compared to the vessels found on the ring centre (Figure 4.9c). A linear regression test indicates that there was a very strong positive linear relationship between the stem and xylem diameter ($y = 1.98+0.69x$, $R^2= 0.879$, $P= 0.000< 0.05$). Stem diameter explained 87.9% of xylem diameter. The xylem diameter of *S. mellifera* from this site increase as the stem size increases (Figure 4.10c).

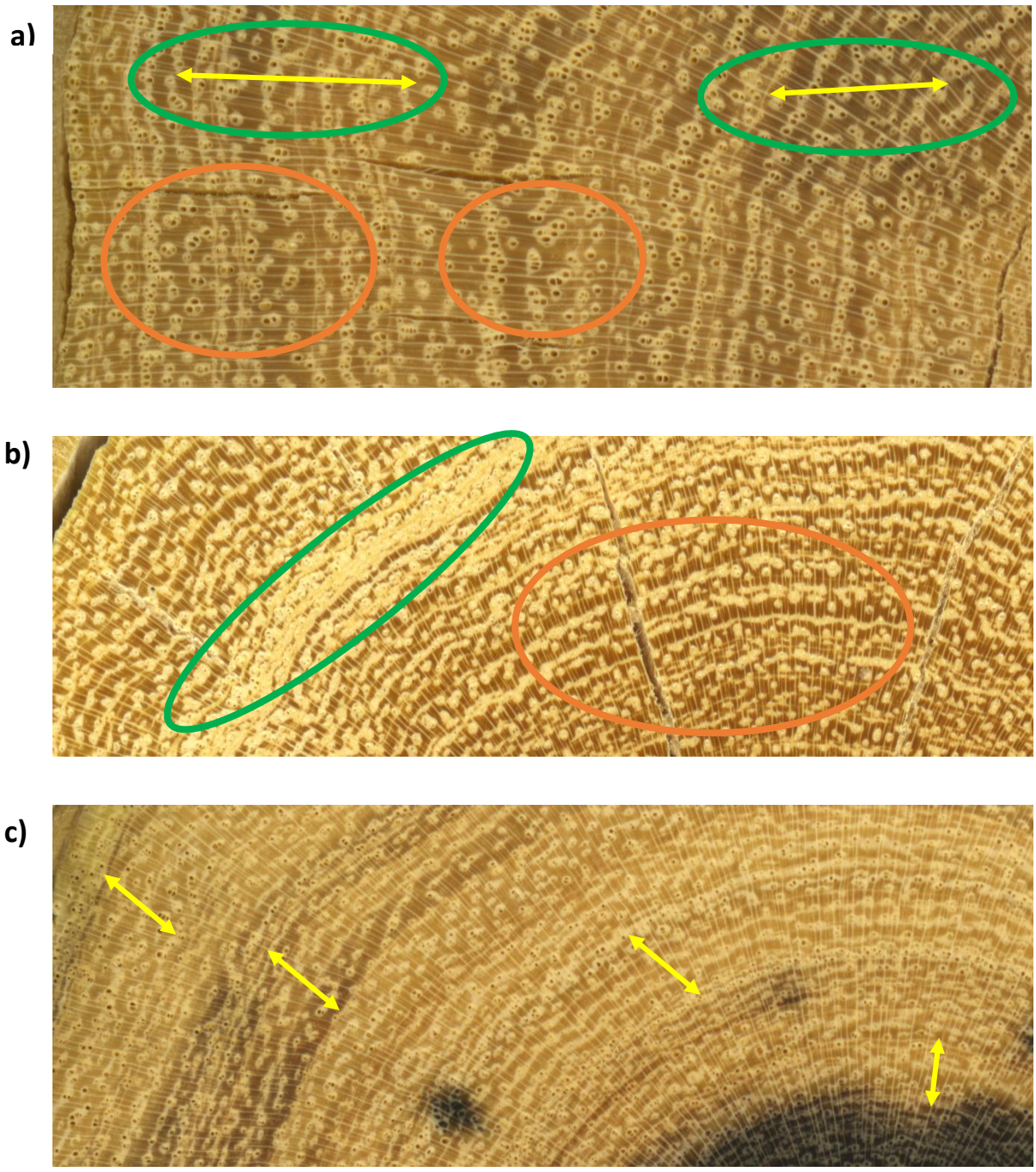


Figure 4.9: Stem discs of *Senegalia mellifera* compared along a rainfall gradient (**a** - Ebenhaezer (250 mm); **b** - Onyoka (450 mm); **c** - John Pandeni (600 mm)). See section 4.2 above for the interpretation of the coloured arrows and circles.

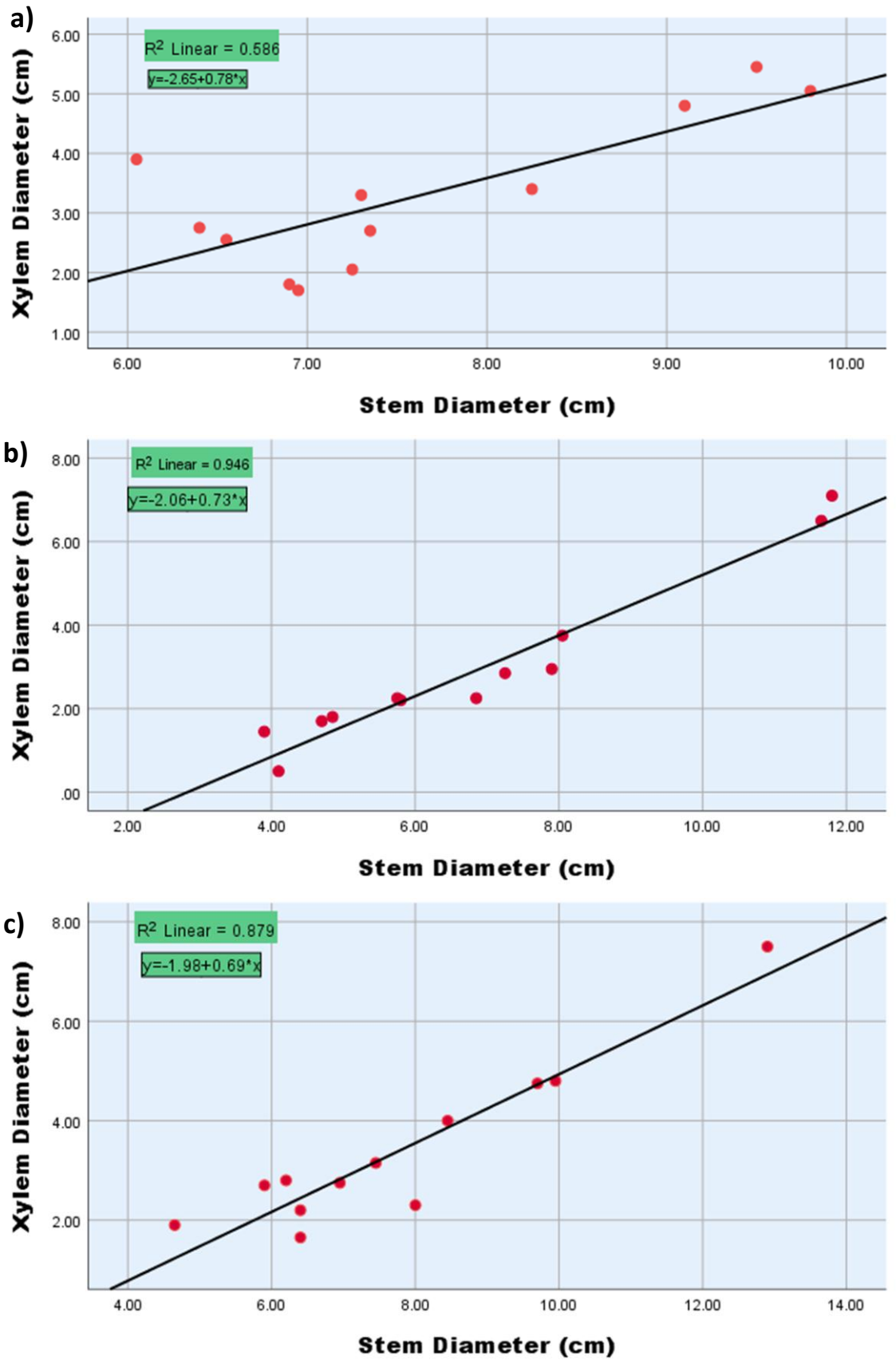


Figure 4.10: Relationship between *Senegalia mellifera* stem diameter (cm) and xylem diameter (cm) along a rainfall gradient (**a** - Ebenhaezer (250 mm); **b** - Onyoka (450 mm); **c** - John Pandeni (600 mm)).

4.4 The relationship between the number of growth rings and stem diameter of the two species along a rainfall gradient

4.4.1 Relationship between the number of *Dichrostachys cinerea* growth rings and stem diameter

4.4.1.1 Ebenhaezer (250 mm per annum)

A linear regression test indicates that there was a strong positive linear relationship between stem diameter and number of growth rings of *D. cinerea* from Ebenhaezer ($y = 1.89+4.56x$, $R^2=0.66$, $P= 0.014< 0.05$). Stem diameter explained 66.0% of numbers of growth rings. As the stem diameter increases, so does the number of rings. This also mean that the stem size of *D. cinerea* from this site does indicate whether the tree is younger or older (Figure 4.11a). The smallest stem disc of *D. cinerea* from this site was 3.2 cm and was the specimen with least number of growth rings (9). The largest specimen was 8.45 cm and it had the highest number of growth rings (40) (Figure 4.11a).

4.4.1.2 Onyoka (450 mm per annum)

There was a weak positive linear relationship between number of rings and stem diameter of *D. cinerea* from Onyoka ($y = 11.6+2.41x$, $R^2= 0.334$, $P= 0.049< 0.05$). Stem diameter explained 33.4% of numbers of growth rings. The number of rings increases as the stem size increases. However, the stem size of *D. cinerea* from this site does not necessarily reveal whether the tree is older or younger (Figure 4.11b). *Dichrostachys cinerea* specimen of 3.15 cm from this site was the smallest; however it was not the specimen with least growth number of rings. The specimen with the

least number of growth rings (11), the stem diameter was 3.95 cm. Although the largest specimen was 7.55 cm, it was not the stem with the highest number of growth rings from this site. The specimen with the highest number of growth rings (30), the diameter was 6.85 cm (Figure 4.11b).

4.4.1.3 John Pandeni (600 mm per annum)

A linear regression test indicates that there was a weak positive linear relationship between stem diameter and number of rings of *D. cinerea* from John Pandeni ($y = 15.18+0.99x$, $R^2= 0.378$, $P= 0.033< 0.05$). Stem diameter explained 37.8% of numbers of growth rings. Although the number of rings in *D. cinerea* found on this site does increase as the stem diameter increases, it does not necessarily suggest the length of time a tree of this species have lived (Figure 4.11c). The smallest stem disc of *D. cinerea* from this site was 3.75 cm and it was the specimen with the least number of growth rings (19). The largest specimen was 10.20 cm, however, it was not the specimen with the highest number of growth rings from this site. The specimens with the highest number of growth rings (24), the diameters were 6.55 cm and 5.15 cm (Figure 4.11c).

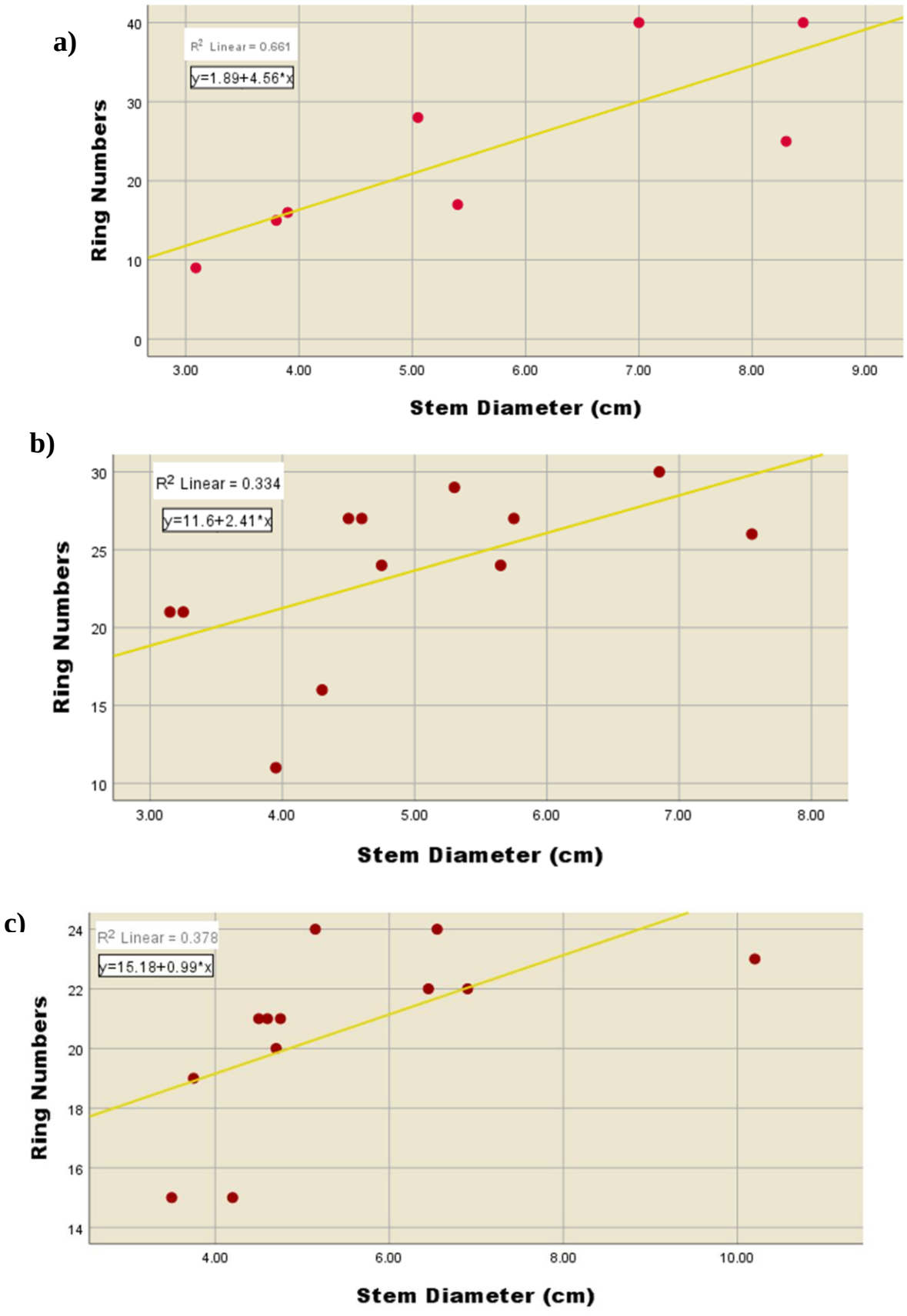


Figure 4.11: Relationship between *Dichrostachys cinerea* stem diameter (cm) and number of growth rings along a rainfall gradient (**a** - Ebenhaezer (250 mm); **b** - Onyoka (450 mm); and **c** - John Pandeni (600 mm)).

4.4.2. The relationship between the number of *Senegalia mellifera* growth rings and stem diameter

4.4.2.1 Ebenhaezer (250 mm per annum)

A linear regression test indicates that there was a moderate positive linear relationship between stem diameter and number of rings of *S. mellifera* from Ebenhaezer (y = 11.67+3.36x, R^2= 0.499, P= 0.010< 0.05). Stem diameter explained 49.9% of numbers of growth rings. The number of growth rings in *S. mellifera* from this site increases moderately as stem diameter increases. However, the stem size does not necessarily indicate whether *S. mellifera* from this site is older or younger (Figure 4.12a). Stem diameter of the smallest *S. mellifera* disc from this site was 6.90 cm, yet it had more numbers of growth rings compared to some of the specimens of the same species, which had larger stem diameter. The specimens with the least number of growth ring (23), the stem diameter were 6.95 cm and 7.25 cm. The specimen with 9.50 cm was the largest one, yet it was not the specimen with the highest number of growth rings from this site. The specimens with the highest number of growth rings (61), the diameter was 9.10 cm (Figure 4.12a).

4.4.2.2 Onyoka (450 mm per annum)

A linear regression test indicates that there was a strong positive linear relationship between *S. mellifera* stem diameter and number of rings from Onyoka (y = 13.48+6.06x, R^2= 0.662, P= 0.001< 0.05). Stem diameter explained 66.2% of numbers of growth rings. The smallest stem disc of *S. mellifera* from this site was 3.90 cm but it was not the specimen with the least number of growth rings. The

specimens with the least number of growth rings (18), the stem diameter was 4.10 cm. The largest specimen was 11.80 cm, and it was the specimen with the highest number of growth rings (59) (Figure 4.12b). The stem size of *S. mellifera* from this site does suggest whether a tree is older or younger (Figure 4.12b).

4.4.2.3 John Pandeni (600 mm per annum)

A linear regression test shows that there was a strong positive linear relationship between *S. mellifera* stem diameter and number of rings from John Pandeni ($y = 11.28+1.42x$, $R^2= 0.618$, $P= 0.002< 0.05$). Stem diameter explained 61.8% of numbers of growth rings. The stem diameter of *S. mellifera* found on this site does suggest whether a tree is younger or older and number of growth rings increase with stem size (Figure 4.12c). The smallest stem disc of *S. mellifera* from this site was 4.65 cm and it had the least number of growth rings (18), but it was not the only specimen with the least number of growth rings. Another specimen with the same number of growth rings (18), the diameter was 6.40 cm. The largest specimen of *S. mellifera* from this site was 9.95 cm, and it was one of the specimen with the highest number of growth rings (Figure 4.12c).

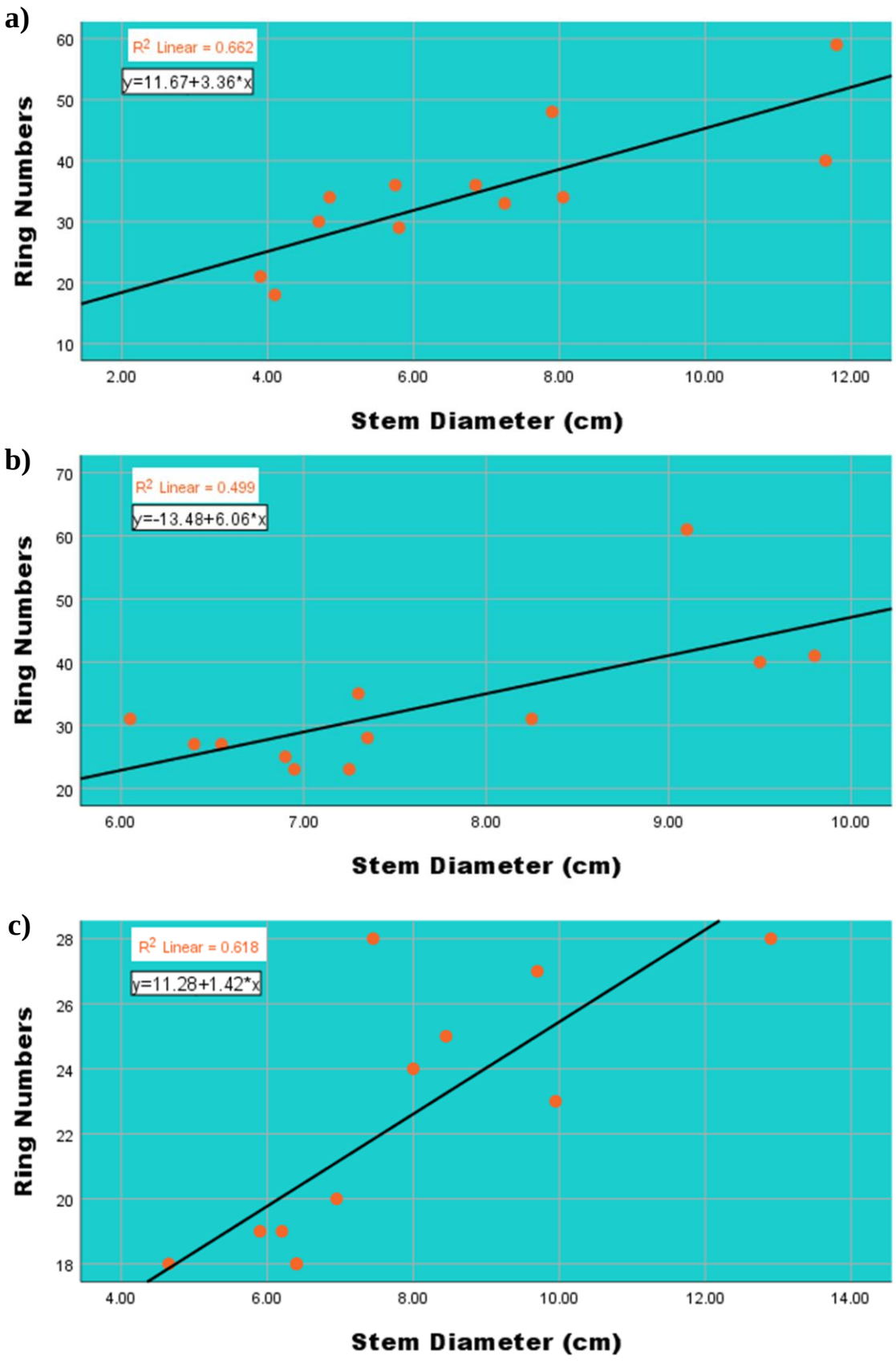


Figure 4.12: Relationship between *Senegalia mellifera* stem diameter (cm) and number of growth rings along a rainfall gradient (**a** - Ebenhaezer (250 mm); **b** - Onyoka (450 mm); and **c** - John Pandeni (600 mm)).

4.5 Comparison of ring growth patterns of *Dichrostachys cinerea* and *Senegalia mellifera* along a rainfall gradient

4.5.1 Ring growth patterns of *Dichrostachys cinerea*

The median ring widths of *D. cinerea* did not differ significantly among sites (H = 4.256, df= 2, P= 0.119 > 0. 05). *D. cinerea* from all the three different sites adds more or less the same amount of woody materials for their secondary growth (Figure 4.13).

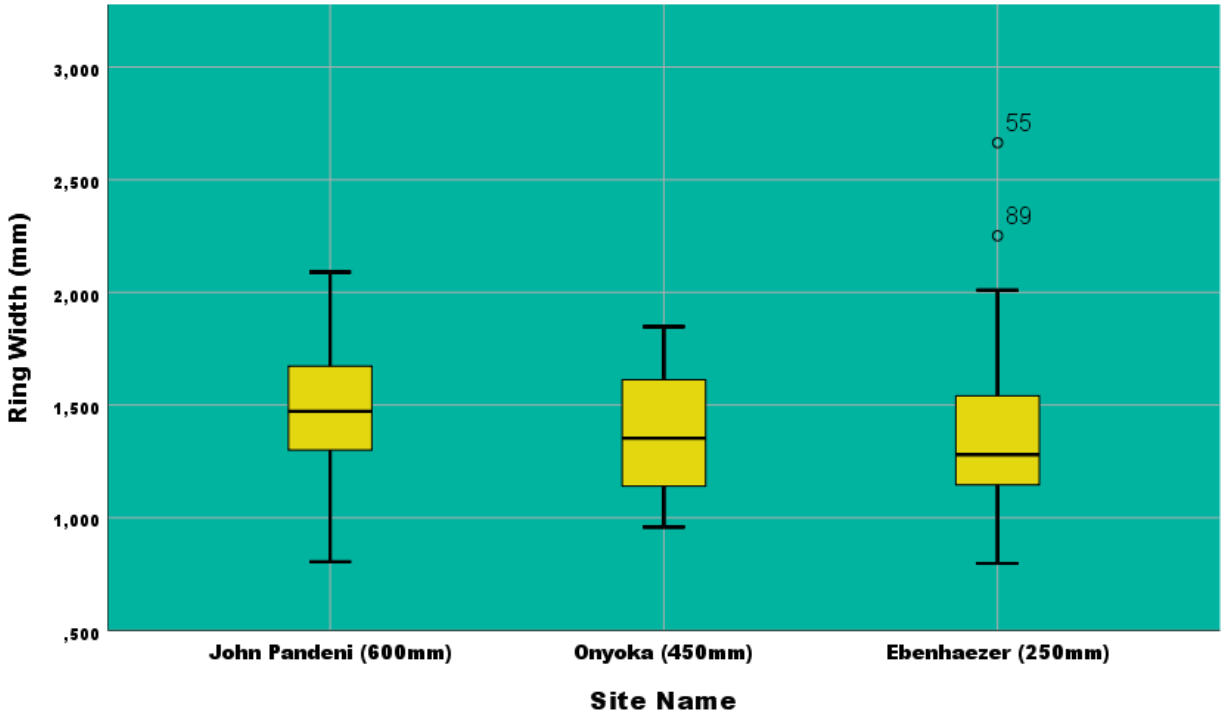


Figure 4.13: Comparison of the median ring width of *Dichrostachys cinerea* trees along a rainfall gradient (John Pandeni, Onyoka and Ebenhaezer).

4.5.2 Ring growth patterns of *Senegalia mellifera*

There was a significant difference in the median ring width among sites (H = 42.366, df= 2, P= 0.000 < 0. 05). Dunn's *post hoc* test indicates that there was no significant difference between median ring width of *S. mellifera* from Ebenhaezer and Onyoka but the median ring width for *S. mellifera* from John Pandeni was significantly higher than from the other two sites (P= 0.008).

Senegalia mellifera from John Pandeni Research Station (where annual rainfall is more than 600 mm), added more woody materials compared to *S. mellifera* from the other two sites that receive less than 500 mm (Figure 4.14).

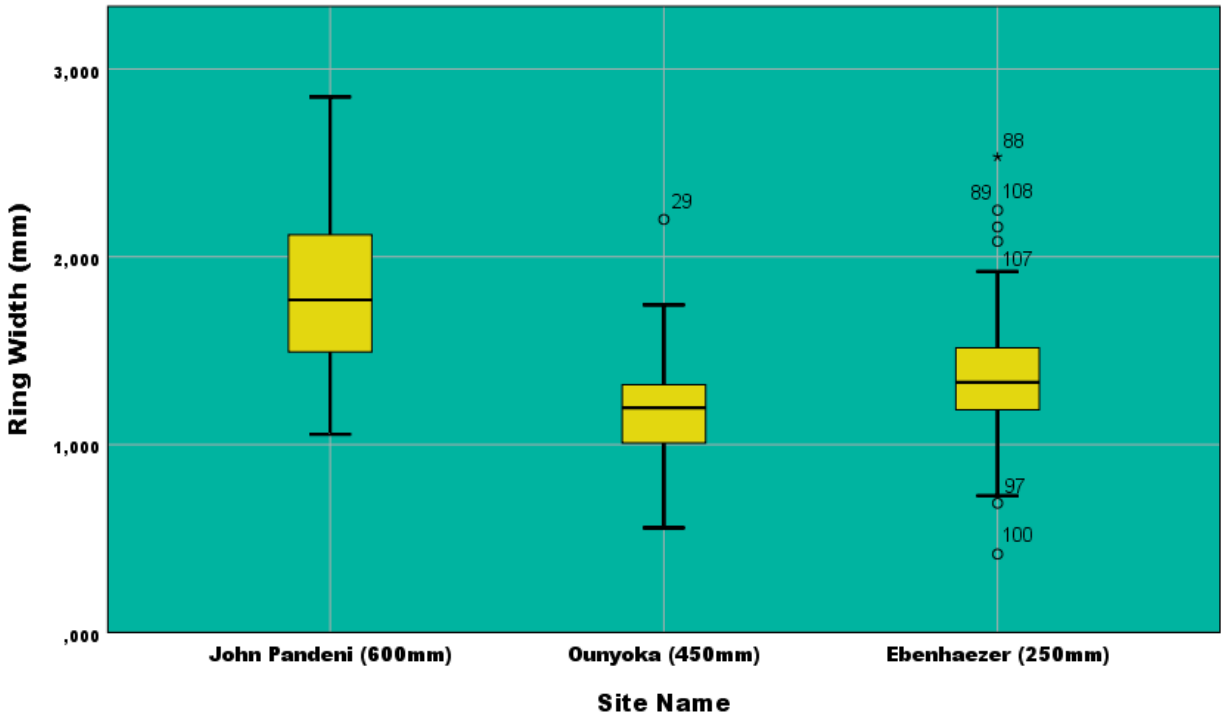


Figure 4.14: Comparison of the median ring width of *Senegalia mellifera* trees along a rainfall gradient (John Pandeni, Onyoka and Ebenhaezer).

CHAPTER 5: DISCUSSION

5.1 Relationship between annual rainfall and ring patterns in *Dichrostachys cinerea* and *Senegalia mellifera* along a rainfall gradient

Dichrostachys cinerea ring width from Ebenhaezer and Onyoka, (both sites receive <500mm of rainfall annually (Figure 3.1 above)), did not correlate with annual rainfall. At Ebenhaezer, rainfall explained only 8.5% of the variations in ring width, and Onyoka rainfall explained only 8.4% of the variations in ring width, meaning the rest of the variation was explained by other factors. In spite of a non-significant linear relationship, the results indicated a positive linear relationship between *D. cinerea* growth ring width and annual rainfall from Ebenhaezer. That suggests that rainfall has a slight influence the growth of *D. cinerea* at Ebenhaezer. According to Hauze & Tran (2015) and (FAO, 2011), *D. cinerea* has a deep tap root which absorbs water from underground, but has poor lateral roots. De Klerk (2004) and Vandenbeldt (1991) stated that genetic variations in root depth and development appear to be considerable in survival strategies in different tree species in the semi-arid environments. According to Gourlay (1995a) rooting profile and the interaction between climate and the geology of the sites are probably the most likely explanations for the considerable variation in relationships between species at different sites and the various meteorological parameters. A non-linear relationships between *D. cinerea* ring width and annual rainfall from Ebenhaezer and Onyoka could mean that *D. cinerea* in sandy soil from these sites also relies on groundwater and not only on top-soil moisture (February & Stock, 1998). According to de Klerk (2004), *Dichrostachys cinerea* on heavier sand soils shows greater sensitivity to the availability of soil moisture and greater changes in

physiological responses during dry years. Both Ebenhaezer and Onyoka are found in the Kalahari Sandy soil (Ndunge, 2018; Mendelsohn et al., 2002).

Borchert et al. (2002, cited in Fichtler et al., 2010) reported that deep-rooting trees in tropical regions in Costa Rica were affected at a lesser extend or were unaffected at all by seasonal drought events as they did not rely on soil moisture because of having a longer tap root which could absorb water from underground to sustain the plant in dry seasons.

In a similar study, Bhugeloo (2014) after a proper cross dating and correlation test also found that *Vachellia nilotica* from northern Kwazulu-Natal, South Africa were not influenced by rainfall. According to Bhugeloo (2014), that was because *V. nilotica* had a well-developed root system which reached the groundwater, enabling it to survive all the years. Contrary, *Senegalia fleckii* (a species known to be a shallow rooting tree) from southern Zimbabwe showed a good visual fit when ring width was plotted against annual rainfall (Gourlay, 1995a & b). CTA and FARA (2011) found a positive linear relationship between the ring width in some *Senegalia-Vachellia* species and annual rainfall in semi-arid environment of Kwazulu Natal, South Africa. The non-significant linear relationship between *D. cinerea* and annual rainfall from Ebenhaezer and Onyoka may mean that rainfall is the most limiting factor for *D. cinerea* on these sites since these sites fall in semi-arid biome and receive little rainfall annually (Steenkamp et al., 2008). A similar study by Hall (1976, cited in Bhugeloo, 2014) found that rainfall patterns limited the growth of *Podocarpus falcatus* in the drier site of Karkloof, KwaZulu–Natal, South Africa.

Figure 4.1a above shows that in 1993, 2000, 2006 and 2007 rainfall was high but *D. cinerea* had a narrower ring. This could be because years of high rainfall occasionally end up in run off and the moisture is not available to the trees (Franke et al., 2013; Nunes et al., 2010, cited in Mapaure, 2016). Although there was high rainfall in the mentioned years, it could be that the high rainfall peak days were fewer to be reflected in the rings of the *D. cinerea* trees (Fichtler et al., 2004). According to Gourlay (1995a & b) growth of many woody species in Southern Africa in any given year in some cases respond more to proceeding rather than to current precipitation. This could explain why *D. cinerea* from Ebenhaezer added more woody materials or had a wider ring, for example in 1992 and 1995 (Figure 4.1a above) when rainfall was low during these years.

A non-linear relationship in *D. cinerea* from Ebenhaezer and Onyoka could also be caused by high temperature and high tree competition for water especially during dry years. Worbes (2002) stated that temperature is a growth limiting factor for trees in semi-arid environments. High temperature leads to increased evapotranspiration rates (Bhugeloo, 2014; Worbes, 2002). Figure 4.1a and b above indicates that an increase in tree growth occurred from 2000-2005 and from 2008-2012 (*D. cinerea* from Ebenhaezer) and from 1988 to 1992 and 1997 to 2002 (*D. cinerea* from Onyoka) and rainfall was high during the same years. According to Bhugeloo (2014) during these years of high rainfall and high growth, temperature could be low, decreasing transpiration rate allowing high tree growth.

Rainfall explained 24.7% of the variations in ring widths at John Pandeni and the rest were explained by other factors. A weak positive linear relationship (R^2=0.247) between ring width and annual rainfall could mean that *D. cinerea* from John Pandeni (600 mm)

is more sensitive to rainfall variation compared to the ones from Ebenhaezer (250 mm) and Onyoka (450 mm). This corresponds with the study by Fichtler et al. (2004) that found *B. africana* from Katima Mulilo (672 mm) to be more sensitive to rainfall variation than the ones from Ondangwa (454 mm). This suggests that in areas of high rainfall, *D. cinerea* trees adapt to higher amounts of moisture for their physiological needs (Feliksik & Wilczyński, 2009).

A positive linear relationship between *D. cinerea* ring width and annual rainfall from John Pandeni might indicate that, *D. cinerea* is sensitive to soil moisture (rainfall). It could use both its tap and lateral roots during years of high rainfall to utilise both soil moisture and groundwater to produce more woody materials resulting in huge ring widths than the rings that formed during dry years when it could rely on groundwater only (Mahecha, 2015). Gourlay (1995b) found several of the correlations calculated in his study of tree growth (*Vachelia karro* from Zimbabwe and *Faidherbia albida; Vachellia tortilis;* and *V. nilotica* from Kenya to be strongly influenced by rooting characteristics in combination with water availability (soil moisture). This could also mean that *D. cinerea* from John Pandeni relies on soil moisture when it is available to its shallower roots. Whenever soil moisture is not available, *D. cinerea* adds less or no woody material (Feliksik & Wilczyński, 2009). Additionally, a positive relationship could suggest that *D. cinerea* has a good uptake of soil moisture when the latter is available, but is poor at groundwater usage (Feliksik & Wilczyński, 2009). According to Novack et al. (2013) a positive relationship found between *D. cinerea* ring width and annual rainfall from John Pandeni (600 mm) may indicate that combination of site climatic conditions are more important to the growth of this species.

Soil type would also affect the reflection of annual rainfall in *D. cinerea*. De Klerk (2004) noted that in sandy soil types, high rainfall events result in deeper moisture penetration leaving the shallow rooted structured plant with no option but to struggle for water or even die off. Because of this, it can be very hard for poor root structured plants like *D. cinerea* (even though *D. cinerea* have a deep tap root, it has poor root system (FAO, 2011)) to cope well because much of the rain water is either lost from the soil as surface run off or benefits other species with well-developed root structure (Fichtler et al., 2004; Stahle et al., 1999). Soils in the area of John Pandeni consist of rock outcrops, Mollic Laptosols, and Chromic Luvisols and Chromic Cambisols which drain slowly (Mendelsohn et al., 2002).

Indistinct, missing and discontinuous or even fake rings could affect the ring width of *D. cinerea* as it was found by Schmitt et al. (1995). Discontinuous rings may be due to periods of none or slow growth that subtropical and tropical trees undergo to survive harsh environmental conditions or by tree movement as it responds to wind (Norström et al., 2005, cited in Bhugeloo, 2014). Fake rings were also found in some specimens of *D. cinerea* from all sites.

Results of this study show that the ring width of *S. mellifera* did not relate significantly to annual rainfall from all the sites along a rainfall gradient (Figure 4.2). Rainfall did not explaine any variations in ring width at Ebenhaezer. However, rainfall explained only 1.1% of the variations in ring width at Onyoka and 11.0% at John Pandeni, meaning the rest were explained by others environmental factors. In spite of a non-significant linear relation, the results indicated a positive linear relationship between *S. mellifera* growth rings and annual rainfall from Onyoka and John Pandeni. That suggest that rainfall may

influence the growth of *S. mellifera* at these sites, but the ones from Ebenhaezer are not influenced by rainfall (Novack et al., 2013). A positive non-significant linear relationship suggests that rainfall is not a limiting factor to *S. mellifera.* However, it might strongly indicate that *S. mellifera* uses two different water sources, groundwater and soil moisture (rainfall) (Verheyden et al., 2004). *Senegalia mellifera* could use groundwater more as a water source than soil moisture (Verheyden et al., 2004). Unlike *D. cinerea*, *S. mellifera* generally has well-developed tap root and lateral root system (Joubert, Zimmermann & Graz, 2009; de Klerk, 2004). Both tap root and multiple lateral roots of *S. mellifera* cover a large total surface soil area and are deeper reaching the groundwater table and this could allow them to exploit soil moisture and nutrients from a large volume of soil (Orwa et al., 2009; FAO, 2008; de Klerk, 2004). This could help them to perform well all years by using soil moisture when it is available and switching to groundwater in dry years and continue to survive and add more woody material. A non-significant linear relationship between *S. mellifera* ring width and annual rainfall is in agreement with the study by Borchert et al. (2002), cited in Fichtler et al. (2010), which reported deep-rooting trees in Costa Rica that they were affected to a lesser extent or were unaffected at all by seasonal drought events as they did not rely on soil moisture due to their well-developed root system. Contrary, Cherubini et al. (2003) found *Arbutus unedo* (a species known to have the shallowest root system in Mediterranean) to be very sensitive to soil moisture (rainfall). The same study explained that deep rooting trees are not sensitive to rainfall, as they are able to reach a more permanent groundwater table. Cherubini et al. (2003) also found other species that are known to have a well-developed root structure (*Fraxinus ornus*, *Quercus cerris* and *Quercus pubescens*) to be less affected by precipitation regime. Moreover, if *S. mellifera* does not rely on soil moisture,

which is a function of rainfall due to its root characteristics, it can be considered to be a drought-tolerant tree species (Fan et al., 2017; Orwa et al., 2009; Bond et al., 2002).

Senegalia mellifera ring widths were smaller compared to the rest of the years from 1999 to 2003 from John Pandeni (Figure 4.2c above) regardless of high rainfall during same years (>450mm/a). This could be because years of high rainfall occasionally end up in run off and the moisture is not available to the trees (Franke et al., 2013). Although there was high rainfall in the mentioned years, it could be that the high rainfall peak days (or high rainfall frequency) were fewer to be reflected in the rings of *S. mellifera* trees (as explained in 5.3.1 above). Figure 4.2b above shows that the rings formed from 1976 to 1980, 1996 to 1999 and from 2006 to 2011 in *S. mellifera* from Onyoka were thick, but rainfall in those same years was low. This could be that *S. mellifera* growth could respond to the preceding high rainfall than to current low rainfall in these years (Nunes et al., 2010; Mapaure, 2011; Gourlay, 1995a). Despite a non-significant linear relationship between *S. mellifera* ring width and annual rainfall from John Pandeni, Figure 4.2c above shows that annual rainfall quantity received on this site had increased since 1988, from < 400 mm/a in 1988 to >600 mm/a in 2013. Interestingly, *S. mellifera* ring width followed rainfall patterns from 2002 to 2009 by forming wider rings when rainfall was high and narrower rings when rainfall was low. Since John Pandeni receives better rainfall (600 mm) compared to the other two sites, *S. mellifera* could take an advantage by using both groundwater and soil moisture when received in large quantities during high rainfall years (Gourlay, 1995a). It might also suggest that *S. mellifera* from John Pandeni is sensitive to rainfall variation compared to the ones from Ebenhaezer (250 mm) and Onyoka (450 mm). Fichtler et al. (2004) also found similar

results for *Burkea africana* from Katima Mulilo (672 mm) and Ondangwa (454 mm). *Burkea africana* from Katima Mulilo were more sensitive to rainfall variation than the ones from Ondangwa. However, *B. africana* root system is incomparable to an encroaching species such as *S. mellifera*, because *B. africana* root structure is very poor and shallow (de Klerk, 2004; Fichtler et al., 2004).

A non-significant linear relationship result found between *D. cinerea* (from Ebenhaezer and Onyoka) and *Senegalia mellifera* (from all sites) ring width and rainfall could possibly be attributed by tree ages. According to (Worbes, 2002) young trees do not follow strong seasonal patterns of growth as much as older trees do. Trees (both *D. cinerea* and *S. mellifera*) of same stem size were found to decrease in number of growth rings along a rainfall gradient (from Ebenhaezer (dry site) to John Pandeni (wet site)). Venegas-González et al. (2017) also observed a non-linear relationship between *Pinus caribaea* ring width and rainfall in high rainfall site. The same author explained that although wood density in many tree species increase in pith-bark direction, these are associated with the unique growth patterns of each species, the growth rates for some trees are high over the first 20 years or in young ages and the growth rate decrease over time. Fichtler et al. (2004) found a negative correlation between annual rainfall and *P. angolensis* in the northern Namibia. Fichtler et al. (2004) explained that a negative correlation to precipitation by many species may be attributed to the exponential increase of plant respiration with increasing temperature. According to Bhugeloo (2014) this would result in a greater loss of assimilated carbon as an energy source.

The reliability of climate reconstructions from tree ring records depends on the quality of the meteorological data as well as on the quality of the tree ring records (Dünisch et

al., 2016). Meteorological data could affect the correlation results of ring width and annual rainfall of the two tree species. Due to the lack of long-term rainfall observations close to Onyoka Site, rainfall data of Otjiwarongo (about 60 km distant from Onyoka) had to be used for the correlation analysis of the tree rings of the two study species. Onyoka is at the same latitude with Otjiwarongo (Mendelsohn et al., 2002), the climate of the two regions are nearly similar according to available maps and data. As for rainfall however, there could be a minor variation, resulting to different rainfall received by the two areas, or the rainfall could be the same but the seasonal rainfall patterns might be different (Novack et al., 2013). Annual rainfall reflected by the ring width of *D. cinerea* and *S. mellifera* from Otjiwarongo might not be the same as the annual rainfall received at Onyoka area. Thus, the correlation between rainfall in Otjiwarongo and the tree ring width of trees at Onyoka could lead to a slight over or underestimation of the impact of rainfall on the annual growth ring of the trees (Dünisch et al., 2016; Poorter et al., 2010). Nevertheless, the study by Dünisch et al. (2016) used meteorological data approximately 800 km away from their study site which had similar climatic conditions, and the ring width of the tree they used (*Swietenia macrophylla*) correlated positively with annual rainfall. Wider rings formed when rainfall was low and narrow rings formed when rainfall was high in all trees of the two species along a rainfall gradient in some specific years could be caused by high and low springtime temperature (Buntgen et al., 2005). According to Buntgen et al. (2005) when spring starts early, the growing season is likely to be longer than usual, causing a tree to grow a wider ring, and when spring starts late, the growing season will be shortened, causing a tree to have a narrower ring. Moreover, narrower rings observed formed in all trees from all sites when rainfall was high could be caused by heavy insect damage. If a tree

loses all or most of its leaves because of insect attack (such as the one on Figure 4.7a above), it will not be able to make food (or enough food) and will grow very slowly that year (https://www.dnr.state.mn.us/forestry/education/foresttreasures/factors.html).

It should also be noted that the sampling methodology for rainfall used for this study since 1940 until 2016 as well as missing data might also have impacted on the quality of the data used for the correlation analysis in this study. February et al. (2006) used COFECHA software to verify and correct cross–dating, however this did not improve the results suggesting that ring width drivers were more complex than just being environmental (Bhugeloo, 2014).

A significant difference was found between *D. cinerea* and *S. mellifera* median ring widths from Ebenhaezer (Figure 4.3 above). The density of *S. mellifera* from the central to the southern of Namibia (Onyoka – Ebenhaezer sites) is high compared to *D. cinerea* (de Klerk, 2004). The median ring width difference between *D. cinerea* and *S. mellifera* from Ebenhaezer may suggests that their growth patterns were linked to the higher frequency, severity and duration of droughts of this site (Natalini et al., 2016). This effect is presumably explained by the efficiency of water consumption by *S. mellifera* in the dry years owing to their deep rooting and efficient vascular systems (Schnitzer, 2005). This may mean that *D. cinerea* from Ebenhaezer only grows back after the end of the dry years, when enough water is available for both *S. mellifera* and other trees (Venegas-González et al., 2017). The increasing uneven of future rainfall patterns as a result of global/local climate change may be expected to benefit *S. mellifera* from the area around Ebenhaezer more than *D. cinerea* and some other trees that compete for water (Turney et al., 2014). Anchukaitis (2017) noted that in semi-arid regions, other

environmental conditions such as humidity, temperature, wind, nutrients and so forth play a role in tree-ring width variation, which are often controlled by precipitation or soil moisture and record information about regional hydro-climate variability. The ring width of one of the two species from the drier site, Ebenhaezer could be influenced by multiple environmental factors causing ring width differences (Anchukaitis, 2017; Turney et al. (2014). There was no significant difference in median ring width between *D. cinerea* and *S. mellifera* from Onyoka and those from John Pandeni. Compared to Ebenhaezer, rainfall is better in these two regions (Figure 3.1 above). This may point out that both species perform well at these two sites. Besides that, this could mean that environmental conditions required by the two species for growth is somehow similar in both sites (Anchukaitis, 2017). This also suggest that among all the growing conditions the two species need, water (rainfall) is the most important factor that controls their growth (Tognetti et al., 2014; Steenkamp et al., 2008).

The results of this study on relationship between *D. cinerea* and *S. mellifera* ring width and annual rainfall illustrate the intimate adaptive relationship between site environments, climate change and/or climate variability and tree growth. The ring width of *D. cinerea* and *S. mellifera* varied between sites across a rainfall gradient and over time (Figures 4.1 to 4.4 above). Wide rings observed in both *D. cinerea* and *S. mellifera* could generally grow during years of optimal climatic conditions (especial rainfall) and the narrow rings might occur in response to poor conditions of these sites (Campelo et al., 2015; Zhang, 2015). The variability of tree ring width observed especially in *D. cinerea* could be caused by moderate and uneven rainfall and a prolonged hot dry years/season due to climate variability or climate change (Olson & Rosell, 2013).

Senegalia mellifera was found to have a narrower ring width in the lower rainfall area compared to the ones found in high rainfall area (Figure 4.14 above). This might explain its excellent adaptation in dry environments making it a problematic species to farmers and other rangeland management communities (de Klerk, 2004).

Tree ring width results in relation to annual rainfall of this study suggest that vegetation responses to climate change in Namibia might vary by species and geographical location. This also entails that the country is not only sensitive to regional environmental changes, but could also be closely linked to global change (Zang, 2015, Walker, 2015).

5.2 The formation and characteristics of distinctive growth rings in *D. cinerea* and *S. mellifera*.

The ring boundaries of *D. cinerea* and *S. mellifera* are separated by narrow marginal parenchyma bands. Marginal parenchyma is a form of axial parenchyma produced by most of the *Vachellia*, *Senegalia* and *Terminalia* species as well as *D. cinerea* at the end or beginning of a growing season (Bhugeloo, 2014). These bands are commonly composed of less than five rows of small parenchyma cells (Steenkamp et al., 2008).

Wood anatomical analysis of *D. cinerea* and *S. mellifera* from all the three study sites unveiled annual formation of distinct growth rings (Figure 3.1 above). Distinct growth rings were marked by marginal parenchyma bands (Figure 4.6a and b above). Marginal parenchyma bands indicate seasonal growth patterns in most *Senegalia*, *Vachellia* and other species in Southern Africa (Gourlay, 1995b). Although several studies (e.g. Maingi, 2006; LaMarche et al., 1979) have highlighted the issues of growth ring within

the *Senegalia-Vachelia* genus and other species in Southern Africa, growth rings defined by marginal parenchyma bands were distinguishable in many *Senegalia-Vachelia* and other species in Southern Africa, such as from Zimbabwe, South Africa and Namibia (Bhugeloo, 2014; Steenkamp et al., 2008; Fichtler et al., 2004; Gourlay, 1995a & b).

According to Zacharia et al. (2017) clear ring formation in tropical and subtropical regions is due to the fact that such species shed leaves every year at the end of each growing season and grow new leaves at the beginning of the next growing season. Since *D. cinerea* and *S. mellifera* are found in sub-tropical/ tropical regions, their growth zones of wood are caused by seasonal variations in cambium action as a result of the alternation of wet and dry seasons (Cherubini et al., 2003). When most tropical trees stop making food due to shedding of leaves at the end of growing season and when new leaves at the beginning of the growing season make food for growth, the process marks the end and/or the beginning of the year in tree rings (Zacharia et al., 2017). The clear tree-ring formation and boundary allowed to be linked directly to annual rainfall of the research sites of this study. Gourlay (1995a; 1995b) stated that the number of rings defined by marginal parenchyma bands with crystalliferous chains could be related to the age of the tree and to climate in the Southern Africa. Several studies in Southern Africa had successfully correlated growth rings of some species with annual rainfall (e.g. February et al., 2006; Fichtler et al., 2004; Worbe, 2004; February & Stock, 1998).

The high density of vessels on the margins and low density on the centre of the growth ring zones in both *D. cinerea* and *S. mellifera* (Figure 4.6a and b above) point to a varying water supply throughout the growth period (Novack et al., 2013). According to Schubert & Jahrem (2015) high density and clumpy vessels indicate water stress during

the beginning and end of the growing season. This suggest that wood structure of the two species record growth responses, which reflect fluctuations in climate (Schubert & Jahrem, 2015).

5.3 Relationship between *Dichrostachys cinerea* and *Senegalia mellifera* stem diameter and xylem diameter along a rainfall gradient

The relationship between heartwood (xylem) diameter and stem diameter were found to be very strong for *D. cinerea* from Ebenhaezer (250 mm) and John Pandeni (600 mm) (Figure 4.7a and c above) compared to the xylem-stem diameter relationship of *D. cinerea* from Onyoka (450 mm), which had a moderate linear relationship. Stem diameter explained xylem diameter very strongly at Ebenhaezer (97.6%), moderately at Onyoka (57.2%) and very strongly at John Pandeni (91.1%). This suggest that stem size of *D. cinerea* from Ebenhaezer and John Pandeni strongly predict its heartwood size, and for *D. cinerea* from Onyoka, the size of the stem does not necessarily tell how large the heartwood diameter is. Also, the relationship between heartwood diameter and stem diameter were found to be very strong for *S. mellifera* from Onyoka (450 mm) and John Pandeni (600 mm) (Figure 4.8b and c) compared to the heartwood-stem diameter relationship of *S. mellifera* from Ebenhaezer (250 mm). Stem diameter of *S. mellifera* explained xylem diameter moderately at Ebenhaezer (58.6%), very strongly at Onyoka (94.6%), and also very strongly at John Pandeni (87.9%). This could be because *S. mellifera* from better rainfall area uses more water compared to the ones found in low rainfall areas (de Klerk, 2004).

A strong relationship between heartwood width and tree stem size was reported by Yang & Hazenberg (1990) in *Populus Tremuloides* Michx from a wet environment. Yang & Hazenberg (1991) reported a weak positive relationship between heartwood and stem diameter in *Pinus sylvestris* and *Pinus nigra* from the same site, although the two species are softwood trees. That is in agreement with the strong relationship found between stem size and xylem diameter of both *D. cinerea* and *S. mellifera* from a high rainfall site, John Pandeni (Figures 4.9c and 4.10c above). A strong and moderate positive linear relationship found between stem diameter and xylem diameter in *D. cinerea* and *S. mellifera* from different sites along a rainfall gradient may explain that, both of the two species form a new ring annually as a result of cambial cell division, however, only a portion of the ring within the inner sapwood is transformed into heartwood in *D. cinerea* from Onyoka and *S. mellifera* from Ebenhaezer (Beauchamp et al., 2012). Large heartwood diameter found in *D. cinerea* from Ebenhaezer and John Pandeni may suggest that the trees of these species from these two sites struggle for water due to high evapotranspiration rate. According to Reyes-Garcı´a et al. (2012) xylem diameters of trees especially those found in semi-arid environment represent an important hydraulic trait, which ensure sufficient water supply from the roots to the leaves. The ability of trees to adjust the hydraulic pathway to environmental cues is key in order to satisfy transpirational demands and maximize growth and survival (Reyes-Garcı´a et al., 2012). Most trees in arid and semi-arid environments have adapted to the dry conditions in many ways including enlarging the xylem diameter as they grow older to increase water absorption, transportation and maintain physical support (Cherelli et al., 2018).

According to Venegas-González et al. (2017) photosynthetic rate and hormone production are reduced in trees during periods of higher water demand, affecting cambial meristem cell division and resulting in xylem tissue differentiation. A moderate relationship found between *D. cinerea* xylem and stem diameter from Onyoka might suggest that water demand is not as high compared to the ones found from Ebenhaezer. A strong and moderate relationship between xylem diameter and stem diameter from the three sites may mean that *D. cinerea* is a poor water user in the semi-arid environment. *Dichrostachys cinerea* from the dry site could enlarge the heartwood size in relation to stem circumference for more water absorption and transportation during years when good rain is received. Venegas-González et al. (2017) found differences in heartwood inter-annual anatomical features between Teak trees and Liana, which exhibited signs of indirect effects of competition for water between the trees and lianas. Such feature differences in heartwood diameter of *D. cinerea* and *S. mellifera* (from Onyoka and John Pandeni, Figures 4.9b and 4.10c above) may represent an adaptive strategy of enhancing hydraulic conductivity efficiency to offset the negative effects on radial growth and vessel abundance as they grow (Venegas-González et al., 2017). Trees with smaller xylem diameter and larger vessels like *D. cinerea* from Onyoka (Figures 4.7b and 4.8b above) and *S. mellifera* from Ebenhaezer (Figures 4.9a and 4.10a above) may maintain reliability whereas larger xylem diameter and clumpy vessel trees like *D. cinerea* from Ebenhaezer (Figures 4.7a and 4.8a above) provide hydraulic conductivity in semi-arid environment (von Arx et al., (2013) cited in Venegas-González et al. (2017). Larger heartwood diameter in *D. cinerea* as it grows which is found in a water-scarce environment might mean that it is very sensitive to atmospheric warming. Some studies have observed heartwood growth patterns in some tree species to have been influenced

by atmospheric warming (e.g. Natalini et al., 2016; Rossi et al., 2011; Deslauriers et al., 2008; Peñuelas et al., 2002). Natalini et al. (2016) noted that xylem size difference may be related to uneven water availability over the years. And this can be true for *D. cinerea* from Ebenhaezer, which receives high rainfall after some years (Mendelsohn et al., 2002, cited in Rodgers, Bilton & Hauptfleisch, 2017) (Figure 4.10a above).

The problem of trees in water stressed environments having a larger heartwood size is that the rate of cell division rate decreases and that increases the tree sensitivity to climatic variability (Syampunganil et al., 2010). Syampunganil et al. (2010) added that trees with larger xylem put themself at risk of death in dry Savanna. This is what was observed to *D. cinerea* from Ebenhaezer. Some of the individual *D. cinerea* trees were found dead-standing in the field (in 2016). Therefore, the *D. cinerea* from Ebenhaezer might be at high risk from climate variability and this might negatively affect their distribution on the southern part of Namibia.

The positive linear relationship found between stem size and xylem diameter of both *D. cinerea* and *S. mellifera* from Onyoka and John Pandeni sites could also be caused by other biological and environmental conditions from these sites, besides moisture availability. For example, Yang & Hazenberg (1991) noted that sapwood and heartwood width of trees varies considerably between families, genera and species. Environmental factors such as site elevation and climate variability (such as temperature, humidity) have some impact on the sapwood and heartwood width and the age of these trees may or may not affect the sapwood and heartwood width (Yang & Hazenberg, 1991). External factors such as site conditions, tree spacing, site elevation and location may

have also played a role in sapwood/heartwood transformation as it was found in a similar study by Yang & Hazenberg (1991).

5.4 Relationship between number of growth rings and stem diameter in *Dichrostachys cinerea* and *Senegalia mellifera* along a rainfall gradient

The results of this study show that there was a positive linear relationship between stem diameter and the number of rings in both *D. cinerea* and *S. mellifera* sampled along a rainfall gradient. Stem diameter of *D. cinerea* explained numbers of growth rings strongly at Ebenhaezer (66.0%), weak at Onyoka (33.4%), and weak for John Pandeni (37.8%). In *S. mellifera* stem diameter explained numbers of growth rings moderately at Ebenhaezer (49.9%), strongly at Onyoka (66.2%), and strongly at John Pandeni (61.8). This may indicate that besides the environmental conditions, the age of the two species is also important for their secondary growth (David et al., 2013). However, some individual small trees of *D. cinerea* from better rainfall sites (Onyoka and John Pandeni, Figure 4.11b and c above) and *S. mellifera* from Ebenhaezer (Figure 4.12a above) were found to be older than the larger trees. According to Yeh & Wensel (2000) stem growth variation is associated with the climatic changes of seasonal precipitation and temperatures for the region, in addition to biological factors. The same authors added that the relationship between climate and tree stem growth changes by densities and species.

The stem diameter of the two species of this study in the research sites could be affected by grazing conditions of both wild and domestic animals (M. L, Hauptfleisch[3], Personal communication). Both sites were situated in livestock farms, which also had some wild animals (see Sections 3.4.1 to 3.4.3 above). Mayer & Stockli (2005) found that *Picea abies* from grazed farms always had lager stem diameter compared to the ones from ungrazed farms.

According to Mayer & Tokli (2005) larger stems were a result of reduced competition between grass, shrub and trees for water. This could also be the reason why *D. cinerea* from Ebenhaezer and *S. mellifera* from Onyoka and John Pandeni had a strong relationship between stem diameter and the number of rings. Smith & Walker (1983) cited in de Klerk (2004) noted that competition between trees and grasses is an important mechanism controlling the size and density of trees.

The larger the tree, the larger the area of resource depletion and the greater its competitive effect on its neighbours (Smit, 2002). This statement can explain the larger stem diameters in relation to the number of rings for *D. cinerea* and *S. mellifera* from John Pandeni. Over-grazing could also result in a well establishment by the two encroaching species observed from John Pandeni. Elsewhere, in Botswana shrub densities showed no consistent change in areas with little or moderate grazing, but in areas with heavy grazing, shrub densities increased (Skarpe, 1990b, cited in de Klerk,

[3]M. L, Hauptfleisch is a Natural Resource Management lecturer from the University of Science and Technology who was part of the OPTIMASS project.

2004). Skarpe (1990b) cited in de Klerk (2004) found an increase in shrub abundance of *S. mellifera* and *Grewia flava* in heavy grazing areas in Botswana.

John Pandeni is an Agricultural Research Station which is inhabited by different types of livestock (Nampa, 2011, p. 1). Sometimes the animals could graze up almost all the grasses (Hauptfleisch, personal communication). Tree stem diameters may be adversely affected by the decreased infiltration of moisture into the soil in grazed sites as a result of reduced grass cover because the water is wasted as surface run-off (Walker & Noy-Meir, 1982, cited in de Klerk, 2004). A strong relationship between the number of rings and stem diameter of *S. mellifera* from Onyoka and John Pandeni could be caused by the species root structure. The smaller *S. mellifera* trees colonize readily (de Klerk, 2004), and they are able to compete favourably with grasses because they rapidly develop a strong tap root and later consolidate by developing a strong lateral root systems (Nesongano, 2018; Sahungwa, 2015). Their ability to fix nitrogen could probably enable them to compete in a wider variety of circumstances (Sahungwa, 2015). This could also be the reason why they are so well adapted and grow into thickets even in areas of less than 300 mm annual rainfall.

De Klerk (2004) explained that the growth and stem size that any individual tree can achieve is a function of the resources to which it has access. In turn, this is a function of available water and nutrient levels and of the proximity and size of neighbouring individuals (de Klerk, 2004). Lager stem neighbour trees will exploit large amounts of water and nutrients around and this leads to poor growth of the smaller neighbouring trees (Smit, 2002). This may suggest that, *D. cinerea* from Onyoka does not cope well with competition for resources and as a result *D. cinerea* grows narrower rings thus

affecting the stem size. According to de Klerk (2004) tree-on-tree competition is very species-specific. Many species can co-exist with little or no competition if they differ in factors such as root distribution (Sahungwa, 2015). A weak relationship found in *D. cinerea* from Onyoka and John Pandeni and *S. mellifera* from Ebenhaezer may be attributed to a delayed stem development, which might be due to shoot die-back that can result from frequent fires and browsed during young age (Syampunganil et al., 2010).

The rates at which trees and grasses use soil moisture are different (de Klerk, 2004). According to Pendle (1982) cited in de Klerk (2004) use of water by grasses appears to be governed largely by atmospheric demand, while that by trees appears to be governed more by soil moisture availability. The same paper further noted that grasses use soil moisture much more rapidly and completely than do trees, with obvious consequences for competition, growth patterns and productivity and this in the long run affects the poor root structured trees like *D. cinerea* (de Klerk, 2004). The ages of both *D. cinerea* and *S. mellifera* might have affected the relationship between the number of rings and their stem diameters. Brotherson et al. (1987) found age predictions to be more accurate for young stems than for older stems for *Cowania mexicana*. Brotherson et al. (1987) also noted that most trees in semi-arid environments grow slower and show narrower widths in their growth rings as they grow older and this affects their stem-age relationships. This could be the reason for a moderate linear relationship between number of rings and stem diameter for *S. mellifera* from Ebenhaezer as most of the *S. mellifera* were found to be older than the *D. cinerea* from the same site. As trees grow older, the inner older rings in some species get compressed and become narrower as more new rings are added (Yang & Hazenberg, 1991). Also, tree growth is not the same

from spring until the end of the summer in tropical regions (Beauchamp et al., 2012). Growth is faster in the spring, stem elongation and diameter growth begin and end at different times, with stem diameter growth continuing longer (https://www.theforestacademy.com/tree-knowledge/annual-growth-rings). This could be the cause of a strong relationship between stem diameter and number of rings in *S. mellifera* from John Pandeni. A young sapling grows much faster than an adult tree (Beauchamp et al., 2012). A cross section of an older tree shows rings that are quite broad at the beginning of its life (in the centre) but that become progressively smaller with time (Forest Academy, n.d). An old tree produces very narrow rings and its diameter and height growth are considerably slower. This affects the relationship between stem diameter and number of rings in many tree species (https://www.theforestacademy.com/tree-knowledge/annual-growth-rings/; David et al., 2013; Beauchamp et al., 2012). This could be possible for the trees from the high rainfall John Pandeni Site, since most of *D. cinerea* and *S. mellifera* trees were younger, maximum number of growth rings were less than 30 (Figure 4.11c and 4.12c above).

5.5 Comparisons of growth ring width between *Dichrostachys cinerea* and *Senegalia mellifera* along a rainfall gradient

5.5.1 *Dichrostachys cinerea*

The results of this study showed that there was no significant difference between the median ring widths of *D. cinerea* from the three sites along a rainfall gradient. This could be because, although *D. cinerea* from the drier sites adds less woody material (narrow rings) annually due to low site rainfall, in years of high rainfall peaks, the

species might add more woody material (huge rings) just like the ones from high rainfall sites (Bowman et al., 2012). As a result, there could be no much difference in the median ring width especially when the trees from the drier site are much older compared to the ones from high rainfall area, which was the case in this study (Bowman et al., 2012). Trees of the same stem size from the dry site were actually older than those from a wet site (see Section 4.4 above). There is a general consensus that in arid regions, it is rainfall that is the dominant factor in determining growth rate (Syampungani et al., 2010). This suggests that regardless of a rainfall gradient (John Pandeni 600 mm; Onyoka 450 mm and Ebenhaezer 250 mm), *D. cinerea* trees have the same water use strategy. Therefore, *D. cinerea* can be considered to be a plant that has poor water use strategies as it uses same amount of water whether it is on wet or drier sites (Novak et al., 2013).

The results of ring patterns along a rainfall gradient of this study correspond with the study by Natalini et al. (2016), which found an insignificant median growth ring size between *Pinus pinea* from different sites that receive different amounts of rainfall. The same study explained that growth of the trees from both sites were enhanced after precipitation during the previous growing season and was limited by water shortage. A possible reason for there being no difference could be that, although these three sites are climatically different and have different mean annual rainfall amounts, they may all be subjected to similar inter-annual variations in the periodicity of seasons (Bhugeloo, 2014). Similarities of median ring width in *D. cinerea* across a rainfall gradient suggests that besides rainfall, variability of other climatic factors control growth of *D. cinerea* at

a large scale irrespective of population distribution and local environmental conditions (Bhugeloo, 2014; Beauchamp et al., 2012).

A non-significant difference in the median ring width for *D. cinerea* may indicate that *D. cinerea* is a slow growing species. Menezes, Berger & Worbes (2003) found a slow growing tree species (*Rhizophora mangle*) to have no difference in their growth ring patterns at different sites but showed a close relationship between the ring width with precipitation. However, Chepape et al. (2011) referred to *D. cinerea* as a fast growing species. Tree height and crown cover also affect tree rings width/growth (Joubert et al., 2014). Shorter trees with more branches add more woody materials compared to the trees that are taller but fewer branches in a similar environment (FAO, 2017). More branches may mean more leaves that will make more food for both primary and secondary growth (Orwa et al., 2009). Compared to *S. mellifera*, *D. cinerea* is characterised as a taller tree with fewer branches (FAO, 2011). Stem height and crown cover could affect the growth pattern of *D. cinerea* at all sites equally regardless of rainfall difference.

5.5.2 *Senegalia mellifera*

There was a significant difference in the median ring widths of *S. mellifera* across a rainfall gradient. The median ring width for *S. mellifera* from John Pandeni Site was higher than those from the other two sites. *Senegalia mellifera* from Onyoka and Ebenhaezer had no median ring width difference. This can mean that *S. mellifera* trees from the high rainfall site at John Pandeni add more woody material to their annual growth rings compared to the ones from the sites with lower annual rainfall. This can

explain the water use strategies by *S. mellifera* (Tognetti et al., 2014). In areas with low water availability it uses low amounts of water and adds little woody material and the species concentrates more on survival and reproduction but when it comes to area with high rainfall, *S. mellifera* uses more water for both growth, survival and reproduction (Nock, Metcalfe & Hietz., 2016; Tognetti et al., 2014). This suggest that *S. mellifera* from John Pandeni grows faster compared to the ones found at Onyoka and Ebenhaezer (Cherubini et al., 2003). This is in agreement with the study by Novack et al. (2013) that found mean ring width difference between *Pinus halepensis* woody plant species from Guardamar, Maigno, Daraca and Slovenia, with different amount of annual rainfall and other environmental conditions. The same authors noted that differences in seasonal precipitation of each site were the cause of patterns of ring width difference in *P. halepensis* from the four different sites.

The median ring width difference for *S. mellifera* could also be caused by rainfall, which varies significantly from year to year (Li et al., 2014). Rainfall is highly localised in Namibia, therefore this could cause the growth and development of this species from the three different sites to differ dramatically (Mapaure, 2016; Steenkamp et al., 2008). Narrow rings do not only signify a lack of water (https://www.theforestacademy.com/tree-knowledge/annual-growth-rings/). A wild fire may have damaged the tree crowns from Ebenhaezer and Onyoka sites and slowed their growth (Forest Academy, n.d). However, the two farms are used for cattle farming and burning of grasses is totally prohibited (F. Kahonzo[4], personal communication).

[4]F. Kahonzo was a livestock manager for farm Ebenhaezer.

Defoliation by insects or fungi could have affected the ring width of the trees from the dry site (Forest Academy, n.d). During field sampling from Ebenhaezer, a number of *S. mellifera* trees had to be abandoned after they were cut because the whole stem centre was damaged by ants. *Senegalia mellifera* from John Pandeni could be more efficient in the utilization of water and light than the ones from Ebenhaezer and Onyoka due to the high amounts of rainfall received by the area, resulting in rapid accumulation of woody materials (Venegas-González et al., 2017; Coetzee, 2010; Mendelsohn et al., 2002).

Olson et al. (2013) explained that tree stem sizes are related to climate. Larger ring widths that form in *S. mellifera* from John Pandeni could be a result of high rainfall received at the site compared to Ebenhaezer and Onyoka (Campelo et al., 2013). *Senegalia mellifera* might use the opportunity of high rainfall (soil moisture) and groundwater at John Pandeni. Therefore, this species which is widespread in arid and semi-arid areas in Africa can be considered as drought resistant (Hauze & Tran, 2015).

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

a) The study on the relationship between ring width and annual rainfall did not support the hypothesis that there is no relationship between rainfall variations and ring patterns in *Dichrostachys cinerea* along a rainfall gradient. However, the results of *Senegalia mellifera* supported the same hypothesis. The study found that the growth ring patterns of *D. cinerea* were influenced by rainfall patterns over the years. This is because *D. cinerea* has a poor root system which makes specie to depend more on sub-surface soil moisture. On the other hand, the study found that rainfall differences across the studied rainfall gradient did not affect the growth ring patterns of *S. mellifera*. This is because *S. mellifera* generally has a well-developed taproot and a lateral root system, which cover a large total soil surface area and are deeper, reaching the groundwater table. This allows *S. mellifera* to exploit soil moisture and nutrients from a large volume of soil even during dry years/seasons. The study concluded that the two tree species differ in their growth response to variations in rainfall over the years. *Dichrostachys cinerea* is more sensitive to rainfall gradients while *Senegalia mellifera* is more adaptable across the same rainfall gradient. As such, *D. cinerea* can be considered a better sensor and indicator of rainfall availability and climate shifts than *S. mellifera*, which tolerates dry climate as much as the wet seasons.

b) The results of this study supported the hypothesis that both *D. cinerea* and *S. mellifera* form distinctive growth rings. The study found out that both species formed distinctive growth rings, which were defined by marginal parenchyma bands. The clear ring formation in *D. cinerea* and *S. mellifera* were due to the fact that the two species shed leaves every year at the end of each growing season and grow new leaves at the beginning of the next growing season (i.e. they are deciduous). The study concluded that both species grow distinctive rings and the characteristics of the rings vary from year to year and by site according to availability of water.

c) The results of the study did not support the hypothesis that there is no relationship between stem diameter and xylem diameter in *D. cinerea* and *S. mellifera* along a rainfall gradient. The relationship between heartwood (xylem) diameter and stem diameter were found to be very strong for *D. cinerea* from Ebenhaezer and John Pandeni compared to the xylem-stem diameter relationship of *D. cinerea* from Onyoka. Also, the relationship between heartwood diameter and stem diameter were found to be very strong for *S. mellifera* from Onyoka and John Pandeni compared to the heartwood-stem diameter relationship of *S. mellifera* from Ebenhaezer. A positive relationship between stem diameter and heartwood diameter found in both species suggest that the trees of these species struggle for water due to high evapotranspiration rate. *Dichrostachys cinerea* from the dry site (Ebenhaezer) could enlarge the heartwood size in relation to stem circumference for more water absorption and transportation during years when good rain is received.

d) The study supported the hypothesis that there is no relationship between numbers of growth rings and stem diameter in *D. cinerea* and *S. mellifera* along a rainfall gradient. However, part of the study result proved that the relationship between *D. cinerea* number of growth rings and stem diameter depend on the amounts of site rainfall. Large stem diameter discs were actually younger than smaller diameter discs from the two sites that receive better annual rainfall (Onyoka and John Pandeni) compared to the ones from dry site, Ebenhaezer. The study concluded that *D. cinerea* stem diameter is influenced more by soil moisture, and not by age. The relationship between *S. mellifera* number of growth rings and stem diameter disproved the hypothesis as they were not affected by site rainfall. Number of growth rings in *S. mellifera* trees from drier site (Ebenhaezer), strongly related to stem diameter as the ones from better rainfall sites (Onyoka and John Pandeni). Between the two species, *D. cinerea* struggles in lower rainfall areas, but *S. mellifera* copes well in low rainfall environment. This could be why the distribution of the two species in south Namibia is highly skewed to *S. mellifera* where *D. cinerea* struggles to establish itself.

e) The study found out that the ring growth patterns of the two species along a rainfall gradient differ and this did not support the hypothesis that the two species show no differences in their ring growth patterns along a rainfall gradient. Regardless of annual rainfall differences received by the trees from the three sites, *D. cinerea* uses the same amount of water to add more or less the same amount of woody materials for their secondary growth at all sites. On the

other hand, *S. mellifera* has a good water use strategy as it uses small amount of water in drier sites to concentrate more on survival and reproduction, but also considers growth more in areas with high rainfall. As a result, *S. mellifera* from John Pandeni grows faster by adding more woody materials each year due to high rainfall compared to the ones from Ebenhaezer and Onyoka. *Dichrostachys cinerea* from Ebenhaezer only grow back after the end of the dry years, when enough water is available.

6.2 Recommendations

a) This study opens up the possibility of further investigating dendrochronology and dendroclimatology as climate change indicators in Namibia. Future research directions should focus on assessing the dendrochronological and dendroclimatological potential of other *Senegalia*, *Vachellia* and other species, which do not grow into thick bushes and are at least older than hundred years for climate change studies. Further studies using the two encroaching species may include root rings and root development comparison between species. Sites and species should be carefully selected to include species that are more sensitive to soil moisture (rainfall) and/or other climatic factors.

b) Rainfall gradient should be extended to a broader rainfall range, from a very high rainfall to a very low rainfall site in order to fully understand site climate variability of the recent past and project the results into future climate models. Since rainfall in Namibia can be patchy, for quality sake of dendroclimatology

results, it is recommended to obtain tree samples close to the weather station (at least <7 Km).

c) Further studies should include isotope results. Isotope studies will possibly provide stronger climate signals, with a high level of precision (Bhugeloo, 2014). Besides isotopes data, ring width, stems and xylem diameters, disturbance events such as fire, insect outbreaks and other biological disturbing factors may be investigated. These further investigations may lead to an increased understanding of local and regional climate change in Namibia and Southern Africa at large.

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