Assessing the dendrochronological and dendroclimatological potential of *Acacia nilotica* (L.) in northern KwaZulu–Natal

By

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As the candidate's supervisor I have/~~have not~~ approved this thesis/~~dissertation~~ for submission.

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July 2014

ABSTRACT

In the face of evidence of predicted climate change, there is a lack of information available on past climatic variability, particularly in southern Africa. Focus on the recent past is critical to understanding the natural variability underlying anthropogenic climate change. High resolution climatic records, such as tree ring series, are crucial to studying past climatic changes. Dendrochronology in the southern hemisphere has not been widely explored due to the perceived lack of annual growth rings in tropical and subtropical tree species. In this study, *Acacia nilotica* (L.) was assessed for its dendrochronological and dendroclimatological potential using 31 stem discs collected from the Bonamanzi Game Reserve, situated in northern KwaZulu-Natal, South Africa. Annual growth rings characterized by terminal parenchyma bands occurred on all samples, however, a number of growth ring anomalies, including missing, false and indistinct growth rings, were commonly encountered. Cross-dating was attempted on all individuals and a 99-yr regional chronology for northern KwaZulu-Natal, ranging between the years 1914–2013 was developed. The regional chronology indicates variable periods of increased and decreased growth of *A. nilotica* throughout the 99 year period, with no coherent growth pattern evident between trees. Correlation analysis was performed with locally averaged climate data, high resolution gridded datasets, the Southern Oscillation Index and the El Niño3.4 index. The weak mean sensitivity indicated by the master chronology suggests that *A. nilotica* is not strongly influenced by environmental variables. This may call into question the reliability of the cross-dating results and master chronology presented, and limit the further application of climate correlation analysis. This research has demonstrated some potential to develop a century long annual tree ring chronology using *A. nilotica* for northern KwaZulu-Natal. A network of tree ring series from southern Africa would extend the spatial and temporal scale of high resolution palaeoclimatic records for the subregion, further increasing our understanding of contemporary climate variability. This study has explored the dendrochronological and dendroclimatological potential of *A. nilotica* thereby contributing to southern African tree ring research.

PREFACE

The experimental work described in this dissertation was carried out in the School of Environmental Sciences, University of KwaZulu–Natal, Westville from February 2012 to January 2014, under the supervision of Dr J.M. Finch.

These studies represent original work by the author and have not otherwise submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

Signed:
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July 2014

Signed:
Dr. J.M. Finch (supervisor)
July 2014

DECLARATION 1 - PLAGIARISM

I, ……………Astika Bhugeloo…………………………..………………………., declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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CHAPTER ONE: INTRODUCTION

1.1. Introduction

Climate change is a natural process operating over geological time scales. In the recent past, however, natural climate regimes have been altered by anthropogenic greenhouse gas emissions, resulting in elevated sea and air surface temperatures, glacial retreat, and sea level rise (Nicholls et al., 1999; Marchant and Hooghiemstra, 2004; McCarroll, 2010). Although there is evidence of accelerated climate change during the mid to late Holocene linked to human activities, there is surprisingly little information available on climatic variability, particularly in Africa (Mayewski *et al*., 2004).

Long term, high resolution climatic information is crucial to studying past climatic variations (Martinelli, 2004). Palaeoclimatic analyses, for example studies of ice cores and fossilized pollen, have provided valuable insights into past climate change by emphasizing climatic fluctuations (Marchant and Hooghiemstra, 2004; Mayewski*et al*., 2004; McCarroll, 2010). There is, however, an urgent call for a greater understanding of the nature and causes of climate change, particularly during the late Holocene (Hughes *et al*., 1982). According to Mayewski *et al*. (2004) and Wanner *et al*. (2008), focus on the recent past is essential to understand the natural variability underlying anthropogenic climate change. Such data can be derived from palaeoecological data which provide quantitative information used to help refine regional climate models, thereby increasing our understanding of regional climate change (Marchant and Hooghiemstra, 2004). Dendrochronology, or tree ring dating, focuses on centennial to decadal time scales and is ideally suited for the study of late Holocene climate variations (Gillooly, 1976; Martinelli, 2004; Wanner *et al*., 2008; Jones *et al*., 2009).

Dendrochronology can be defined as the systematic dating technique of chronological layers of annual growth rings in trees (Stokes and Smiley, 1968; Walker, 2005). In recent years, dendrochronology has received increased attention in palaeoclimate studies, due largely to its provision of annually resolved records on decadal to centennial time scales that are vital to global climate change studies (Hughes, 2002; Martinelli, 2004; McCarroll and Loader, 2004; Jones *et al*., 2009; Gebrekirstos *et al*., 2011). Dendroclimatology can be defined as dendrochronological studies that use climatic information from tree rings to study past and present climates and climatic variability (Hall, 1976). James Hutton’s principle of uniformitarianism is a fundamental keystone of tree ring based climate reconstructions (Hughes, 2002; Carrer and Urbinati, 2006). Applied to dendroclimatology, this means that tree–growth climate relationships are steady over time so that accurate inferences about the nature of past climates can be made from statistically derived tree–ring calibration (Hughes, 2002; Carrer and Urbinati, 2006). Dendroclimatology provides several proxy climate records, such as temperature and precipitation that can be used to study the effects of global phenomena such as El Niño and La Niña (Gillooly, 1976; Hughes *et al*., 1982; Trouet, 2004). These proxy records can be accurately assigned to a date and location, making the information provided by tree rings invaluable in climate change research (Hughes *et al*., 1982; Martinelli, 2004).

Tree ring studies in southern Africa are somewhat limited owing to the lack of annual rings in many subtropical and tropical tree species (Lilly, 1977; February *et al*., 2006, Jones *et al*., 2009; Stahle, 1999a). Tree ring analysis in the tropics and subtropics is therefore restricted to areas with distinct wet and dry seasons (Worbes, 1992). However, there have been numerous attempts at tree ring research in southern Africa (Hall, 1976; Curtis *et al*., 1978; McNaughton and Tyson, 1979; Dunwiddie and LaMarche, 1980; Gourlay, 1995a February and Stock, 1998; 1999; Trouet *et al*., 2001; 2010; 2012; Vogel *et al*., 2001; Fichtler *et al*., 2004; Norström *et al*., 2005; February *et al*., 2006; Grundy, 2006; Robertson *et al*., 2006; Therrell *et al*., 2006; 2007; Patrut *et al*., 2007; Stahle *et al*., 1999b; Steenkamp *et al*., 2008; Remane, 2013). The presence of growth ring anomalies such as indistinct and missing rings, and the lack of climatically sensitive trees have restricted dendroclimatic research in southern Africa (Trouet, 2004; Jones *et al*., 2009). Despite this, several of these studies have demonstrated the potential of tree ring analysis as a palaeoclimatic proxy, increasing the need for further dendroclimatological research in the subregion (Jones *et al*., 2009).

The genus *Acacia* belongs to the family Fabaceae and is widespread across southern Africa (Gourlay, 1995a; 1995b). Previous studies have revealed that *Acacia* species form distinct growth ring boundaries, allowing for age determination via ring counts (Gourlay, 1995a; Gebrekirstos *et al.,* 2009). Moreover, the population density and structure and the distribution of many species of *Acacia* are determined by climate variables (Steenkamp *et al*., 2008). This suggests that members of the genus *Acacia* may prove to be reliable palaeoclimatic archives, particularly for reconstructing precipitation patterns (February *et al*., 2006; Gebrekirstos *et al*., 2009). Additionally, according to Hughes *et al*, (1982), the *Acacia* genus may have strong dendroclimatological potential due its medium–tall height and occurrence in woodlands. Results from a study by February *et al.* (2006) suggest that the genus *Acacia*, including *Acacia nilotica* in South Africa, may hold dendrochronological potential. *A. nilotica* has not been thoroughly studied as a prospective palaeoclimatic proxy in the southern hemisphere, thus providing a novel research opportunity allowing for the expansion and refinement of our understanding of climate change of the recent past.

1.2. Aim and objectives

To assess the potential of *Acacia nilotica* (L.) for dendrochronological and dendroclimatological research with a view to develop a palaeoclimate reconstruction for the northern KwaZulu–Natal region. Detailed objectives are:

i. To extract ring samples from *A. nilotica* trees and to process discs such that growth rings can be easily identified and counted;
ii. To acquire temporal information from the samples through microscopic tree ring counts resulting in age determination of each tree;
iii. To assess the dendrochronological potential of *A. nilotica* through cross–dating procedures and develop a master chronology for *A. nilotica;*
iv. To attempt to correlate the master chronology with instrumental climatic data to assess the dendroclimatological potential of *A. nilotica*; and
v. To produce a palaeoclimatic reconstruction for the region

1.3. Thesis outline

This chapter has introduced and set the context for dendrochronological and dendroclimatological research in southern Africa and on the genus Acacia. The research aim and objectives have been outlined. Chapter two provides a review of dendrochronological and dendroclimatological research in southern Africa. The development of tree ring research in southern Africa is discussed in detail. Chapter three discusses theoretical methodologies applied in tree ring research. These include cross–dating, standardisation and characterisation of tree ring chronologies. Additionally, the history of tree ring research is discussed as well as its advantages and limitations. Chapter four provides a detailed description of the research methodology. Results are presented and described in chapter five, including growth ring identification, age determination, the presentation of average growth curves and the master chronology and responses of growth rings to climate. This is discussed and interpreted in chapter six. In conclusion, chapter seven provides a synthesis of findings and reviews the extent to which the dendrochronological and dendroclimatological potential of *A. nilotica* have been assessed. Future research directions are suggested.

CHAPTER TWO: REVIEW OF DENDROCHRONOLOGICAL AND DENDROCLIMATOLOGICAL RESEARCH IN SOUTHERN AFRICA

2.1. Introduction

Tree ring records are archives of past climate change that have played a fundamental role in in attempts to determine recent climate variation (Martinelli, 2004; Jones *et al.*, 2009; Gebrekirstos *et al.*, 2011). During each growing season, tree rings are added radially by forming new layers of wood cells on the inside of the cambium that indicate prevailing climatic conditions during the growing season (Gebrekirstos *et al.*, 2011). Climatologists and ecologists are increasingly finding the field of dendroclimatology helpful as evidence for recent global warming, for the determination of climate sensitivity on regional and near–hemispheric scales and for researching characteristics of climate variability on annual to decadal time scales (Hughes, 2002; Jones *et al.*, 2009).

Dendroclimatalogical studies in southern Africa[1] have been restricted due primarily to the poor dendrochronological potential of African tree species (Jones *et al.*, 2009). Subtropical and tropical trees are often perceived as lacking annual growth rings due to regularly high temperatures and warmer winters (Steenkamp *et al.*, 2008). However, a few tree ring records have been produced from subtropical and tropical regions, suggesting that some species of subtropical and tropical trees are climatically sensitive (Martinelli, 2004; Jones *et al.*, 2009). Increased pressure on forest resources due to logging and other disturbances restrict the availability of older trees that would be more suitable for dendrochronological studies (Jones *et al.*, 2009). This has restricted palaeoenvironmental reconstructions for the region, due to the limited length of records provided (Holmgren *et al.*, 1999; Meadows, 2001). The development of tree ring research in southern Africa is important as dendroclimatology is vital in understanding previous changes in the Earth's climatic system which will help predict

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[1] Southern Africa is defined as Namibia, Botswana, Zambia, Mozambique, Swaziland, Lesotho and South Africa. This may also be defined as the region south of the Kunene River, which flows south from the Angolan highlands to the Namibian border and then west along the Namibian border until it joins the Atlantic Ocean (Wellington, 1955).

the sensitivity of southern Africa to future climate change (Norström *et al*., 2008; Jones *et al*., 2009; Fichtler *et al*., 2010).

This chapter will provide a history of dendroclimatological studies conducted in southern Africa, summarized in Table 2.1 for comparison.

2.2. Development of dendrochronology and dendroclimatology in southern Africa

The development of tree ring chronologies in the northern hemisphere has been extensive due to the distinct nature of growth rings of trees growing in temperate and boreal latitudes (Wimmer and Vetter, 1999; Martinelli, 2004; Trouet, 2004). 'There is a distinct lack of dendrochronological studies from countries such as South Africa, due to the perceived lack of annual growth rings in tree species from subtropical, tropical and Mediterranean climates' (Figure 2.1) (Lilly, 1977; February, 1992; Wimmer and Vetter, 1999; Martinelli, 2004).

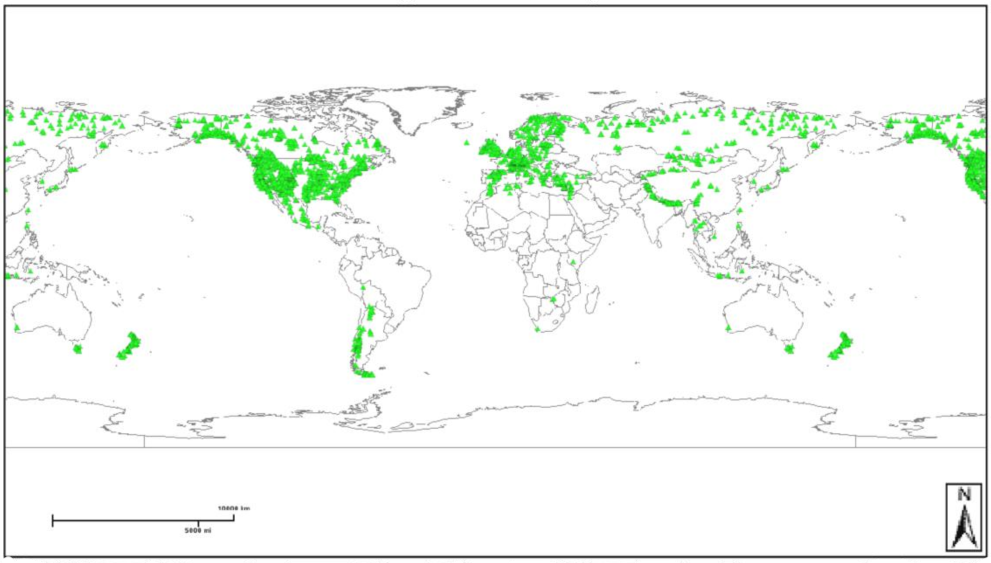

Figure 2.1: Worldwide distribution of tree ring chronologies submitted to the International Tree Ring Databank (ITRDB) (represented by shaded areas) (after ITRD, 2014)

Dendrochronology in southern Africa is hampered mainly by the lack of suitable tree species (Hughes *et al*., 1982). Due to the lack of large indigenous trees in South Africa, the location of suitable specimens becomes difficult (Lilly, 1977). However, this can be overcome by sampling species from families that have previously displayed dendrochronological potential in the tropics and subtropics, such as *Podocarpus*, and by sampling species that have been described in the literature as having anatomical features, such as marginal parenchyma and growth ring porosity. The ideal situation would be to select sites where moisture availability is the dominant factor controlling growth, however due to the lack of suitable trees species this cannot always be strictly adhered to (Lilly, 1977; Hughes *et al*., 1982). Selecting sites that are close to meteorological stations that can provide long term weather records is important (Wimmer and Vetter, 1999).

The climate of southern Africa is complex with a number of key climatic drivers (Lee-Thorp *et al*., 2001; Scott and Lee-Thorp, 2004; Nash and Meadows, 2012). The two main systems that dominate climatic processes in the region are the westerlies and the easterlies (Scott and Lee-Thorp, 2004). The reconstructions of Holocene palaeoclimates in southern Africa show the influence of Milankovitch solar cycles and local effects on the global thermohaline system (Holmgren *et al*., 2003; Scott and Lee-Thorp, 2004). The interaction of southern Africa's atmospheric and oceanic circulation systems influence the distribution of biomes and the distinction of C_3 and C_4 grasses in winter and summer rainfall regions (Scott and Lee-Thorp, 2004). Due to the aridity of the region, moisture is considered to be an important climate variable (Scott and Lee-Thorp, 2004; Nash and Meadows, 2012). The thermohaline circulation influences the dryness of southern Africa by regulating heat transfer from the Indian Ocean into the Atlantic Ocean on the east coast of southern Africa, through the Agulhas current (Holmgren *et al*., 2003; Scott and Lee-Thorp, 2004). The effects of general circulation patterns combined with topography that causes seasonal differences in precipitation with varying amounts of precipitation received across the region (Lilly, 1977; Hughes *et al*., 1982).

Rainfall variability in southern Africa is linked to the El Niño Southern–Oscillation (ENSO) phenomenon (Richard *et al*., 2001). Dry conditions generally occur over southern Africa during warm ENSO events, or the El Niño phase of the cycle, and moist conditions occur during the La Niña phase. Sea surface temperatures (SST) anomalies have been linked to southern African rainfall. The Southern Oscillation Index (SOI) and El Niño3.4 index are continuous indices of southern oscillation regulation, in relation to El Niño and La Niña phenomena in the Pacific Ocean (Ropelewski and Halpert, 1987; Hulme *et al*., 2001).

Rainfall seasonality affects the formation of growth rings (Hughes *et al*., 1982). Discontinuous rings are likely to occur in trees in summer rainfall areas due to seasonal rainfall while a rainfall event in temperate climates will result in trees that have growth rings with distinct boundaries (Hughes *et al*, 1982; Jones *et al*., 2009).

Despite these problems, there have been attempts at tree ring research in southern Africa (Table 2.1). The results of some of these studies have contributed to the ITRDB (Figure 2.1), showing that southern African tree species can in fact contribute to our understanding of climatic variability of the recent past.

2.3. Dendrochronological and dendroclimatological studies in southern Africa

The following section will provide a review of dendrochronological and dendroclimatological work that has occurred throughout southern Africa (Figure 2.2).

2.3.1. Genus *Acacia*

Gourlay (1995a) conducted dendrochronological analysis on 40 trees comprising 16 *Acacia* species from eastern and southern Africa. The species that were analysed were *Acacia albida* (L.), *Acacia burkei* (L.), *Acacia caffra* (L.), *Acacia erioloba* (L.), *Acacia galpinni*(L.), *Acacia gerrardii* (L.), *Acacia goetzei*(L.), *Acacia heroensis* (L.), *Acacia karroo* (L.), *Acacia nigrescens* (L.), *Acacia pilispina* (L.), *Acacia polyacantha* (L.), *Acacia rehmanniana*(L.), *Acacia robusta* (L.), *Acacia welwischii* (L.), and *Acacia xanthophloea* (L.) from Kenya, Malawi, Somalia, South Africa and Zambia and Zimbabwe. X–ray densiometry and a scanning proton microscope were used to examine growth rings. Distinctive patterns of periodic tree wounding at documented time intervals of *A. karoo* was used as a method to determine a growth pattern following felling of the trees. Marginal parenchyma bands were examined in relation to the callus that had formed where the tree was wounded. Results of this method, indicated by the production of xylem, revealed that the wounded *A. karoo* trees did not produce wood during winter months. All methods indicated that marginal parenchyma bands indicate seasonal growth patterns in *Acacia* species. There was a strong correlation between annual rainfall and mean ring width and minimum temperature and mean ring width, suggesting that *Acacia* species may be climatically sensitive.

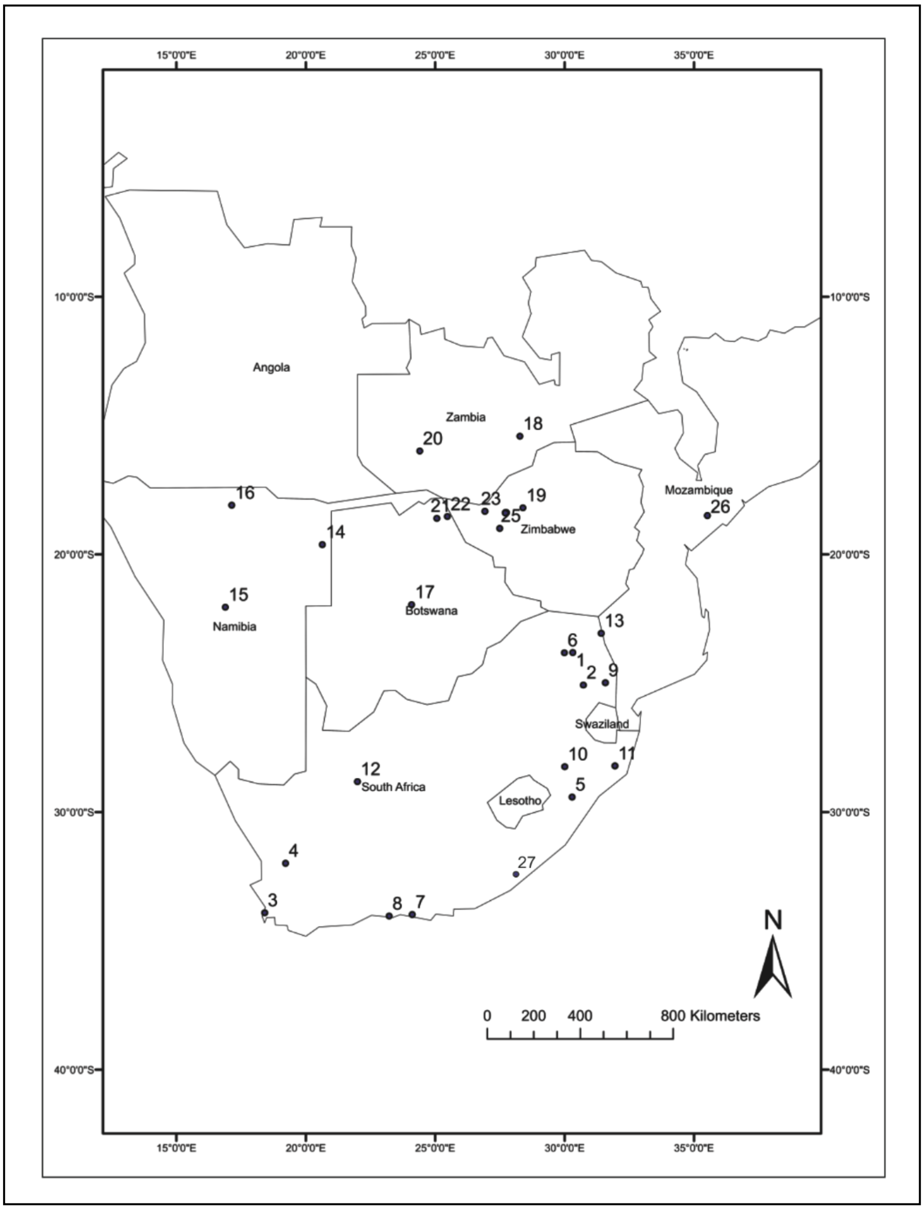

Figure 2.2: Location of tree ring sites in southern Africa based on site numbers in Table 2.1 (1 – Limpopo, South Africa; 2 – Soutpansberg, South Africa; 3 – Cape Town, Western Cape, South Africa; 4 – Die Bos, South Africa; 5 – Karkloof, KwaZulu–Natal , South Africa; 6 – Magoebaskloof, South Africa; 7 – Witelsbos, South Africa; 8 – Knysna, Western Cape, South Africa; 9 – Skukuza, South Africa; 10 – Drakensberg, KwaZulu–Natal, South Africa; 11 – Hluhluwe Imfolozi, KwaZulu–Natal, South Africa; 12 – Kalahari; 13 – Kruger National Park, South Africa; 14 – North–eastern Namibia; 15 – Namibia; 16 – Northern Namibia;17 – Botswana; 18 – Zambia; 19 – Western Zimbabwe; 20 – Mihozhe, Zambia; 21 – Luampa River, Zambia ; 22 – Pandamatanga, Botswana ; 23 – Sikumi, Zimbabwe; 24 – Mzola, Zimbabwe; 25 – Matabeleland, Zimbabwe; 26 – Mozambique; 27 – Eastern Cape, South Africa)

Nineteen *A. erioloba* trees were selected for dendrochronological analyses from two habitats in the Kgalagadi Transfrontier Park in the Kalahari, South Africa (Steenkamp *et al*., 2008). Annual growth rings were identified in all samples. Radiocarbon ages and ages by ring counts showed good consistency, although the ring counts often underestimated the tree age by ~11%. Trees were estimated to be between 17 and 210 years old. Tree age and stem circumference showed a positive relationship, suggesting that the age of *A. erioloba* may be extrapolated from stem circumference. There was no significant difference in growth rates between trees at both habitats. *A. erioloba* may have some dendrochronological potential due to the presence of annual growth rings and the correlation between radiocarbon ages and ring counts (Steenkamp *et al*., 2008).

February *et al*. (2006) analyzed six *Acacia nilotica* and six *Acacia nigrescens* (L.) trees from Hluhluwe–Umfolozi Park in Zululand, South Africa. Cross–dating between species or between trees from the same locality was not successful due to indistinct growth rings, especially in *A. nigrescens*. This suggests that the determinant factors of ring width for both species are not environmental. Ring counts estimated an age of 29–36 years for *A. nilotica* and 46–83 years for *A. nigrescens*. Radiocarbon analysis was performed on the samples to validate ring counts. Radiocarbon ages indicate that *A. nilotica* samples were between 45–49 years old and the *A. nigrescens* sample was 75 years old. The radiocarbon ages and ring counts do not match suggesting that naturally grown *Acacias* may lack dendrochronological potential. However, the ring counts did provide approximate age estimates.

2.3.2. Genus *Adonsonia*

Adonsonia digitata (L.) (Baobab) is a tree which reaches unusually large sizes and may have high dendrochronological potential due to its old age, greater than 1000 years BP (Robertson *et al*., 2006; Patrut *et al*., 2007). Patrut *et al*. (2007) suggests that counts of annual growth rings are not a reliable method for dating baobabs as growth rings may not be visible in older trees and the occurrence of internal hollows prevents accurate age estimates. Baobabs are therefore only reliably dated by radiocarbon dating of wood samples (Patrut *et al*., 2007). The absorbent nature of the fibrous wood of the baobab may prevent the formation of annual growth rings (Robertson *et al*., 2006). A felled baobab from north–eastern Namibia in 1960 had an estimated radiocarbon age of ~950 cal years BP (Robertson *et al*., 2006). Patrut *et al.* (2007) used accelerator mass spectrometry to date the tree which had a radiocarbon date between AD 1420–1440. Growth rates of stems indicate the growth of the baobab had decreased drastically in the past 500–600 years. This is attributed to a decrease in rainfall in central southern Africa over the same time period. Radiocarbon dating suggests that the drought may have begun as early as 1400–1500 years BP. Baobab disease may be responsible for the decrease in growth rates in the tree over the past 500–600 years BP (Patrut *et al.*, 2007).

Stable isotope techniques, particularly analysis of carbon isotope values, may prove to be a reliable method when using the baobab as a climatic archive (Robertson *et al.*, 2006). Robertson *et al.*, (2006) extracted a stem disc from a fallen baobab tree at Kruger National Park and an increment core from a living tree at Skukuza, to determine whether growth rings in the baobab are annual and thereby assessing their dendrochronological potential. Samples from both trees were taken for radiocarbon testing. The dead baobab was dated at AD 1981–2002, i.e. 21 years. The living tree had a known age of 30 years. Robertson *et al.* (2006) suggested that ring width chronologies may not provide reliable age estimates for the baobab due to the swelling and distortion properties of the tree. However, carbon isotope values were positively correlated with monthly precipitation, suggesting that baobabs are climatically sensitive to precipitation events. Isotope analyses may therefore prove to be more useful in long term chronology building with high temporal resolution. Robertson *et al.* (2006) does strongly recommend that the results and conclusions drawn from this study are duplicated before the baobab can be considered a reliable tree species for use as a climate proxy.

2.3.3. Genus *Brachystegia*

Trouet *et al*. (2001) collected eleven *Brachystegia spiciformis* (L.) samples from a study site in western Tanzania. There was a high occurrence of locally absent rings leading to varying results between ring counts of radii. This made cross–dating difficult, which could be overcome by sampling at different tree heights.

Trouet *et al*. (2006) sampled three sites in western Zambia. Fifteen to eighteen samples of *B. spiciformis* were taken from each site. Full stem discs were used as they are more suitable than increment cores due to the presence of wedging rings. Older trees have a higher incidence of ring wedging compared with younger trees (Trouet *et al*., 2006). Chronologies were developed for each site and ranged from 27 years to 57 years (Trouet *et al*., 2006). A regional chronology was also developed. Meteorological series and the regional chronology were compared with each other. The results of the correlation analysis suggest that *B. spiciformis* is sensitive to climatic factors.

Further studies on *B. spiciformis* in Zimbabwe were conducted by Grundy (2006). Results indicated that *B. spiciformis* produced clear growth rings. However, the high variability of annual rings within each sample complicated cross–dating difficult which posed problems in developing a chronology for the region.

Syampungani *et al*. (2010) investigated *Brachystegia floribunda* (L.), at two sites in Zambia. Distinct growth rings were present among all species in the study. Indistinct rings were present on some samples, which was attributed to competition between plants for light and nutrients.

Trouet *et al*. (2010) developed five tree ring chronologies for the miombo woodland in south central Africa. Three dry sites and two wet sites were selected and between nine to 34 full stem discs of *B. spiciformis* were collected. Distinct growth rings were present in all samples. Cross–dating was successful for all samples from all sites. Chronologies developed ranged between 43 years to 149 years. Results indicated a negative response of tree growth to ENSO. Future studies should focus on developing longer chronologies for the miombo region, particularly where ENSO effects are the strongest, to allow the investigation of temporal ENSO variability.

B. spiciformis from Zambia was further researched by Trouet *et al*. (2012). Cambial growth periodicity of six trees was investigated using the pinning method, i.e. the bi–weekly pinning of trees using pins or nails inserted into the bark through to the cambium of trees to produce a cambial response, that can be monitored by the cambial markings of the pins and nails, was employed. Results indicated that cambial growth was synchronous across all samples but did not correspond to the beginning and end of the rainy season, although cambial growth did only occur during the rainy season. The length of the growing season lasted approximately 3–4 months and corresponded to the core of the rainy season. The sudden onset of heavy rainfall did not result in the formation of false rings. However, the results from this study may be attributed to low sample replication.

These studies suggest that *Brachystegia* has high dendrochronological potential which is attributed to the clear growth rings of all the specimens, successful for cross–dating of Zambian specimens and successful correlation between climate and tree ring chronologies (Grundy, 2006; Trouet *et al*., 2006). However, trees found in stressful environments, may be more reliable indicators of climatic change as growth is likely to be limited by fewer environmental variables (Grundy, 2006).

2.3.4. Genus *Breonadia*

Norström *et al*. (2005) sampled two *Breonadia salicina* (L.) trees from the Limpopo province of South Africa. Radiocarbon dating and wiggle match dating were performed on wood samples to develop a 620 year chronology for the eastern part of the Limpopo region. There may be some reservations about the reliability of this chronology as only two samples were used in this study. Carbon isotopic analyses revealed a correlation between variations in precipitation and xylem. A negative correlation between $\delta^{13}C$ values and annual precipitation was evident for the 20th century (Norström *et al*., 2005). Growth rings did not match accelerator mass spectrometry (AMS) dates, indicating that growth rings were not annual or seasonal. Wiggle match dating (WMD) was used to produce an age model for the years AD 1375–1995 using nine AMS dates from each sample. Annual rings were formed during periods of rapid growth. Subtropical trees survive harsh environmental conditions by experiencing periods of non–growth where no growth rings are produced or slow periods of growth where growth rings are too thin for identification (Norström *et al*., 2005). It is possible that *B. salicina* trees used in this study underwent very slow periods of growth and the rings were unidentifiable. Missing rings were therefore attributed to slow growing seasons and were indicated by the difference in the number of years between radiocarbon dates in accordance to WMD and the number of visible microscopic rings (Norström *et al*., 2005). Norström *et al*. (2008) conducted further research on the trees via radiocarbon analyses and WMD. Only two samples were analysed once again and had an age of 547 years and 620 years.

Both specimens showed similar carbon isotope compositions throughout their life spans, although the trees grew at different localities (Norström *et al*., 2005). This suggests that the carbon isotope composition of both trees is influenced by common sources, indicating that regional moisture levels were a driving force for both trees (Norström *et al*., 2005; Norström *et al*., 2008). $\delta^{18}O$ values differed considerably between the two trees, likely due to differences in microclimatic factors as the trees were sampled from two different sites (Norström *et al*., 2008). Co–variation in $\delta^{13}C$ and $\delta^{18}O$ signals in high resolution sequences for both trees indicates that *B. salicina* is not limited by moisture levels (Norström *et al*., 2008).

The *B. salicina* record indicates that dry conditions were prevalent in Limpopo during the mid 1500's (Norström *et al*., 2005). Moist conditions occurred during the 1600's followed by dry conditions during the 1700s (Norström *et al*., 2005). This was followed by a wet period during the 1800's (Norström *et al*., 2005).A slow growth rate, attributed to cool, dry conditions occurred between AD ~1600–1900. A negative relationship between $\delta^{13}C$ and $\delta^{18}O$ occurred at low sample resolution coincided with periods of slow growth due to changes in climatic conditions. Future studies should use more samples and closer sampling for AMS dates and $\delta^{13}C$ analysis.The use of *B. salicina* as a palaeoclimatic proxy was hampered by the weak correlation between $\delta^{18}O$ signals between the two trees. Such a detailed study has the potential to produce a longer chronology for climate in northern South Africa, where palaeorecords are rare.

2.3.5. Genus *Burkea*

Fichtler *et al*. (2004) determined the dendrochronological potential of *Burkea africana* (L.) from two sites in northern Namibia (Ondangwa and Katima Mulilo). Microscopic analyses revealed the presence of distinct, annual growth rings resulting in successful cross–dating. The *B. africana* chronology for Ondangwa was 110 years old and 65 years old for Katima Mulilo. *B. africana* showed a strong correlation with precipitation at both sites. A strong correlation was present between ring width and climate. Tree growth at Ondangwa correlated with the ENSO phenomenon. There was a decrease in tree growth during La Niña years and an increase in tree growth during El Niño years, indicating the positive relationship between tree ring width and rainfall. Results concluded that *B. africana* is climatically sensitive and has high dendrochronological potential.

2.3.6. Genus *Isoberlinia*

Trouet *et al*., (2001) collected 13 *Isoberlinia tomentosa* (L.) samples from a study site in western Tanzania in which *Brachsytegia* was investigated. The high occurrence of locally absent rings led to varying ring counts across radii. However, 38 year tree ring chronology was developed for this species. A strong correlation was found between mean ring width and monthly precipitation values, monthly maximum air temperature values and monthly SOI values. This suggests that these variable are strong determinates of annual growth rings in *I. tomentosa*.

Isoberlinia angolensis (L.) in Zambia was analysed by Syampungani *et al*. (2010). The occurrence of distinct growth rings on all samples suggests that *Isoberlinia* from Zambian miombo woodlands may have dendrochronological potential.

2.3.7. Genus *Julbernadia*

Syampungani *et al*. (2010) investigated *Julbernadia paniculata* (L.) at two sites in Zambia. The species exhibited distinct growth rings. *J. paniculata*, therefore, has potential for dendrochronology in miombo woodlands in Zambia.

2.3.8. Genus *Millettia*

Remane (2013) analysed the dendrochronological and dendroclimatological potential of an important timber species, *Millettia stuhlmannii* (L.), from Mozambique. Successful cross–dating within and between trees suggested the annual nature of growth rings. A chrornology of 111 years was developed. Correlation analysis of indexed ring widths with climate data showed a significant relationship between tree growth and precipitation. Analysis of mean annual increment indicate that *M. stuhlmannii* takes approximately 75 years to reach the legally required cutting diameter of 40 cm at breast height. There was a significant relationship between stem diameter and percentage of heartwood, with the percentage of heartwood remaining stable from a diameter at breast height of ~33 cm. Additionally, heartwood width was positively correlated with total stem diameter, total stem diameter area, cambial age, number of rings present in heartwood, heartwood area and mean annual increment. Results from this research suggest that more work should be done to improve diameter growth models and volume increment models, so as to fully utilize *M. stuhlmannii* as a timber species. Results also suggest that this species may be used to accurately reconstruct past climatic conditions in Mozambique.

2.3.9. Genus *Mimusops*

Stable carbon isotopes of *Mimusops caffra* (L.) of known age from KwaZulu–Natal were investigated by Hall *et al*. (2009). Radiocarbon analyses were first used to confirm the presence of annual growth rings of *M. caffra*. $\delta^{13}C$ analyses revealed a negative correlation between temperature and $\delta^{13}C$ values and a positive correlation between precipitation and $\delta^{13}C$ values, suggesting that *M. caffra* is more sensitive to precipitation than temperature. Cross–wavelet analysis between isotope results and environmental drivers was performed to further examine the relationship between precipitation and $\delta^{13}C$ values. The $\delta^{13}C$ values are particularly responsive to events such as droughts and cyclones, indicating that climatic and environmental conditions may be inferred from stable carbon isotope analyses of *M. caffra*.

2.3.10. Genus *Podocarpus*

Hall (1976) conducted a dendrochronological study on a single specimen of *Podocarpus falcatus* (L.) from the indigenous Karkloof forests in the KwaZulu–Natal Midlands. Initial studies showed that the specimen, felled in 1916, had 597 growth rings of varying widths indicating climate sensitivity (Hall, 1976). Annual growth rings were recorded, despite the presence of missing and false rings. This study was the first attempt at dendrochronology in the KwaZulu–Natal region (Hall, 1976). It was further stated by Hall (1976) that future dendrochronological studies using a greater number of specimens to ensure successful cross–dating will be necessary in order to develop a precise chronology for the region. The variability of ring widths in the *P. falcatus* specimen supports the assumption that precipitation is a limiting factor for tree growth in the Karkloof (Hall, 1976). The Karkloof forests experiences summer rainfall and occasional snow and frost during winter (Hall, 1976). Periods of 16–20 year rainfall oscillations are visible in the Hall (1976) record, supporting statistical analyses by Tyson (1971; 1972) and Tyson and Dyer (1975). The work carried out by Tyson and his colleagues suggests rainfall oscillations occur in southern Africa which varies geographically. Tyson and Dyer (1975) state that a quasi–20 year rainfall oscillation exists in the summer rainfall regions of southern Africa. Furthermore, periods of slow growth of the *P. falcatus* specimen that occurred during the 1820s, 1840s and 1860s are supported by historical records of famine that is likely to have occurred due to drought (Hall, 1976).

Vogel *et al*. (2001) performed radiocarbon dating on the *P. falcatus* sample that had been previously examined by Hall (1976). Radiocarbon dates matched the ages that were derived by counting the annual growth rings. Vogel *et al*. (2001) determined the tree to be 774 years old. Rainfall patterns of the Karkloof were inferred from the tree ring widths despite it being a single sample, as its location on a hill–slope allowed it to accurately record precipitation patterns (Vogel *et al*., 2001). There were low precipitation patterns in the Karkloof before

AD 1520. High rainfall occurred during the 17th century followed by a decline in precipitation patterns from AD 1705–1800. Wet weather occurred again between AD 1800–1818 followed by dry conditions until the tree was felled in AD 1916.

Curtis *et al.* (1978) conducted dendrochronological analysis on a single *P. falcatus* specimen felled in the Woodbush Forestry Reserve in Magoebaskloof, Limpopo, South Africa. The specimen was dated between 110–120 years old using ring counts but was assumed to be older due to the occurrence of missing rings. However, complete section analysis suggests that the *P. falcatus* specimen averaged an age of 128 years for the three upper stem sections. An age of 136 years was determined for the basal trunk of the specimen but was probably an overestimate due to the complexity of counting growth rings near the pith of the lowest subsample. The specimen had a complicated ring structure during the first 56 years of growth and a high number of converging rings between AD 1873–1903. A uniform growth pattern was present between AD 1904–1956 followed by a period of hindered ring growth between AD 1957–1967, attributed to either climatic or environmental stresses.

Stem discs from 12 *P. falcatus* trees from the Witelsbos Forest in the Western Cape of South Africa were analysed for their dendroclimatological potential by McNaughton and Tyson (1979). Ages were determined for seven of 12 samples and pith ages were established for five out of the seven samples due to faint rings, converging rings and poor sample quality (McNaughton and Tyson, 1979). Trees aged between 80 years to 205 years. There was no evident relationship present between tree age and diameter, height or bole length (McNaughton and Tyson, 1979). Cross–dating of the five samples showed that there was limited growth during the 1860s, 1930s and 1960s, indicated by decreasing ring widths. Wider ring widths show periods of increased growth during the late 19th century and early 20th century (McNaughton and Tyson, 1979). Comparisons of ring widths with instrumental records suggested that moisture is a growth limiting factor for *P. falcatus* (McNaughton and Tyson, 1979). However an inverse relationship between moisture and tree growth was observed for the majority of the period between 1844–1952 when there was increased tree growth during dry conditions. Tree growth decreased during wet conditions between 1853–1861 (McNaughton and Tyson, 1979). The southern Cape region experiences a complex rainfall regime compared with the rest of South Africa (McNaughton and Tyson, 1979). If rainfall records for the Cape specifically are compared with growth rings, it follows that there are periods during which there is an inverse relationship between moisture and tree growth and vice versa. Enhanced tree growth and dry conditions prevailed between 1938–1940 and 1958–1960. Limited tree growth and wet conditions prevailed between 1940–1966 (McNaughton and Tyson, 1979). Moisture was a growth limiting factor between 1914–1918 with enhanced growth during the wet period between 1918–1924 (McNaughton and Tyson, 1979). Further studies are likely to suggest a complex relationship between climatic and environmental conditions and tree growth of *P. falcatus* in the Witelsbos area (McNaughton and Tyson, 1979).

February and Stock (1998) collected whole trunk cross sections of eight *Podocarpus latifolius* (L.) and six *P. falcatus* samples of unknown age from Hakerville, Knysna, South Africa for analyses of their dendrochronological potential. There was a significant correlation in tree ring counts for both *Podocarpus* species, suggesting that the rings are annual and are affected by similar climatic factors. Cross–dating between trees was not possible due to the presence of inadequately defined, locally absent and converging rings. Climate reconstruction was therefore not possible. February and Stock (1998) suggest that future research efforts should focus away from *Podocarpus* species and move towards developing improved methods for cross–dating.

Hall *et al*. (2008) conducted stable carbon isotope analysis on modern charcoal from *P. falcatus* from the Eastern Cape of South Africa and archaeological charcoal from and *P. latifolius* specimens from Sibudu Cave, KwaZulu–Natal, South Africa. The main factor affecting the isotopic combustion of charcoal is combustion temperature. Although overall δ^{13}C values in charcoal decrease through combustion, the environmental signals initially recorded in wood tissue are still preserved. Although it is possible that past climates can be inferred from δ^{13}C values in archaeological charcoal, it is necessary to establish modern equivalents from different environments to establish a range of adaptive strategies available to a particular species. Comparisons between modern and archaeological charcoal suggest that δ^{13}C values are preserved in *P. falcutus* specimens. The δ^{13}C values of the modern and archaeological charcoal are in accordance with proxy environmental signals from previous studies. Environmental conditions at Sibudu Cave were warm and moist at ~70 ka followed by cooler and drier conditions around ~58 ka. Warmer conditions returned to Sibudu Cave around 48 ka. Results from δ^{13}C analyses conducted by Hall *et al*. (2008) therefore suggest that archaeological charcoal are good preserves of rainfall, humidity and temperature and can be used as a palaeoenvironmental proxy.

2.3.11. Genus *Protea*

February (1994) analysed archaeological charcoal from *Protea caffra* (L.) and *Protea roupelliae* (L.) from Collingham Shelter and Mhlwazini Cave in the Drakensberg of KwaZulu–Natal, South Africa. Vessel diameter of the two species correlated to rainfall whereas vessel density was negatively correlated to rainfall. These results indicate that arachaeological charcoal may be used to reconstruct rainfall patterns. The analysis of archaeological charcoal was therefore used to estimate patterns of wet and dry periods at the Drakensberg. Results suggest that a wet phase occurred during ~2400 years BP followed by cyclical wet and dry conditions. Dry conditions prevailed between ~1000 years BP to present day. However, there was a slightly moist period during ~200 years BP. February (1994) suggests that increased dating resolution will allow for a more detailed reconstruction of the past climate.

2.3.12. Genus *Pterocarpus*

Palaeoecological studies conducted on *Pterocarpus angolensis* (L.) from Zimbabwe represented the first regional reconstruction of rainfall in tropical Africa based on a 200 year tree ring chronology from AD 1796 to 1996 (Therrell *et al*., 2006). The rainfall patterns correlate well with regional ENSO patterns (Therrell *et al*., 2006). Additionally, the rainfall reconstruction correlates with instrumental rainfall records from the 1960's, indicating an arid period during this time (Therrell *et al*., 2006). Tree ring reconstructed rainfall records and documentary evidence indicate the occurrence of a severe drought between AD 1868 to 1869and between AD 1882 to 1886 (Therrell *et al*., 2006). Historical evidence suggests that drought conditions were often widespread from the Kalahari and these conditions coincide with the tree ring records from Zimbabwe (Nash and Endfield, 2002; Therrell *et al*., 2006). For example, the reconstructed drought period between AD 1882–1888 coincides with widespread drought conditions in Botswana between AD 1884–1886 (Nash and Endfield, 2002; Therrell *et al*., 2006). Tree ring records indicate that most of the 20th century (AD 1897–1982) was characterized by moist conditions (Therrell *et al*., 2006). The rainfall reconstruction suggests a strong link between ENSO patterns and rainfall trends in Zimbabwe (Therrell *et al*., 2006). Spectral analysis reveals periods of variance at decadal and multi–decadal frequencies (Therrell *et al*., 2006). In addition, the reconstruction correlates well with national maize yields in Zimbabwe between AD 1970–1996 (Therrell *et al*., 2006). Results indicate that *P. angolensis* could be used as a valuable palaeoclimatic proxy for southern Africa (Therrell *et al*., 2006).

Therrell *et al.* (2007) further developed tree ring research on *P. angolensis* from nine sites across southern Africa to determine tree age, diameter increment, the relationship between heartwood and stem diameter and the relationship between local rainfall and mean tree diameter growth. The sites were Mihozhe, Luampa River, Pandamatanga, Sikumi, Mzola, Matabelele Land, Kruger National Park, Mozambique and Soutpansberg. Analyses of diameter revealed a slow growth rate for all samples, indicating that *P. angolensis* trees require approximately 100 years to arrive at the requisite harvesting cutting diameter of ~35–40 cm at breast height. *P. angolensis* is greatly prized for its timber in southern Africa (Therrell *et al*., 2007). However studies such as this one indicate that trees need to grow for many years to be adequately harvested posing problems on the timber industry, such as the financial cost of maintaining *P. angolensis* trees over long periods of time. A positive relationship between stem diameter and heartwood was reported, indicating an increase in cutting diameter would increase the percentage of heartwood in timber, which is desirable in the timber industry (Therrell *et al*., 2007). Differences in growth rates were recorded between individual trees and between trees at different sites. There was a positive relationship recorded between annual diameter and seasonal rainfall across all sites. Median tree ages ranged between 80 years old to 140 years old with mean diameter ranging between 28.4 cm to 40 cm. Median tree age and median tree diameter exhibited a positive relationship but was variable across sites. This suggests that median tree diameter may be used as an indicator of tree age at the stand level but may prove to be unreliable across the range of the species.

Fichtler *et al.* (2004) determined the dendrochronological potential of *P. angolensis* from Odangwa and Katima Mulilo in northern Namibia. The species exhibited distinct, annual growth rings. A 79 year longchronology was developed for Ondangwa. A 60 year long chronology was developed for Katima Mulilo. There was a strong correlation between ring width and climate at both sites. *P. angolensis* showed a stronger correlation with temperature and relative humidity at Katima Mulilo than Odangwa. Tree growth was positively correlated with the ENSO phenomenon at both sites. Additionally, a positive relationship between tree ring width and rainfall was noted. Results concluded that *P. angolensis* is climatically sensitive and displays dendrochronological potential.

Stahle *et al*. (1999b) assessed the dendrochronological and dendroclimatological potential of *Pterocarpus angolensis* (L.) from the Sikumi and Mzola forests in western Zimbabwe. Growth rings appeared to be annual in nature, characterized by continuous bands of initial parenchyma. The occurrence of annual growth rings was further supported by successful cross–dating among trees at each site. A 120 year chronology (1876–1996) was developed for Sikumi and a 124 year chronology (1873–1997) was developed for Mzola. The chronologies significantly correlated with each other over the common period between 1876–1996. Chronologies developed for each site were significantly correlated with rainfall during the wet season between 1901–1990. *P. angolensis* is considered an important timber species in southern Africa. The dendrochronological and dendroclimatological potential of *P. angolensis* displayed by this study can help inform studies of the growth and yield of the species under various ecological and management conditions.

2.3.13. Genus *Widdringtonia*

Dunwiddie and LaMarche (1980) conducted dendroclimatological analysis on increment cores from 28 living *Widdringtonia cedarbergensis* (L.) trees and 19 stem discs from dead *W. cedarbergensis* trees from Die Bos site in Cape Town, South Africa. This study was the first dated annual tree ring–width index chronology for the southern hemisphere. A site chronology for the period AD 1564–1976 was developed via cross–dating. The presence of frost rings, i.e. rings that show frost damage, in the samples were used as marker years for cross–dating as these rings dated consistently between samples. Frost rings may be considered to be reliable indicators of age when used for cross–dating as they are unusually wide and most trees are less susceptible to frost damage after they have reached several diameters in width (Dunwiddie and LaMarche, 1980). Climatic response functions were calculated using multivariate analysis and instrumental climate data from nearby weather stations (Dunwiddie and LaMarche, 1980). The analysis revealed that the growing season for *W. cedarbergensis* was likely to be between October to March. The response function of ring widths to both monthly maximum temperature and monthly precipitation values showed a negative response of tree growth to spring and summer during some months. A negative response to precipitation and a positive response to high temperatures occurred in other months. The conflicting findings suggest that further chronologies need to be developed covering different habitats and geographic areas in the region. A fire frequency record was noted during the study. Fire scars were present on several stumps from dead trees on rings dated AD 1872 (Dunwiddie and LaMarche, 1980). There was a marked increase in growth in the living trees, indicated by ring widths, suggesting an increase in growth due to a fire release effect. This study demonstrated the potential for dendroclimatological analyses of long tree ring records from southern Africa.

Stable carbon isotope analyses were conducted on cores from six *W. cedarbergensis* trees from Die Bos in the Cedarberg Mountains, Cape Town (February and Stock, 1999). This was the first high resolution carbon isotope chronology developed for the southern hemisphere (February and Stock, 1999). An annual chronology for the site was previously developed by Dunwiddie and Lamarche (1980). February and Stock (1999) reported that stable carbon isotope results showed that there was no correlation between monthly and annual rainfall data from a nearby weather station, suggesting that water is not a key variable limiting the growth of *W. cedarbergensis*. A 77 year $\delta^{13}C$ chronology was developed for *W. cedarbergensis* and shows a decline in $\delta^{13}C$ over recent years (February and Stock, 1999). This is attributed to anthropogenic carbon emissions as the increase in biospheric carbon dioxide alters the $\delta^{13}C$ values present in the air which is reflected in tree ring cellulose or wood (February and Stock, 1999). Previous studies indicate that there is a declining trend in $\delta^{13}C$ values in tree rings since the beginning of the Industrial Revolution (February and Stock, 1999). Stable carbon isotope results indicated that the $\delta^{13}C$ ratio remained relatively stable between 1900–1949. $\delta^{13}C$ values decline significantly between 63–35 cal years BP (1949–1977). The $\delta^{13}C$ chronology correlates with ice core records and tree ring chronologies from the northern hemisphere and southern hemisphere. This was the first chronology with annual resolution to track the effects of global warming in the southern hemisphere (February and Stock, 1999).

Figure 2.3 below displays the minimum, maximum and mean age per tree species, showing that the majority of tree species studied in southern Africa, are of a limited age range.

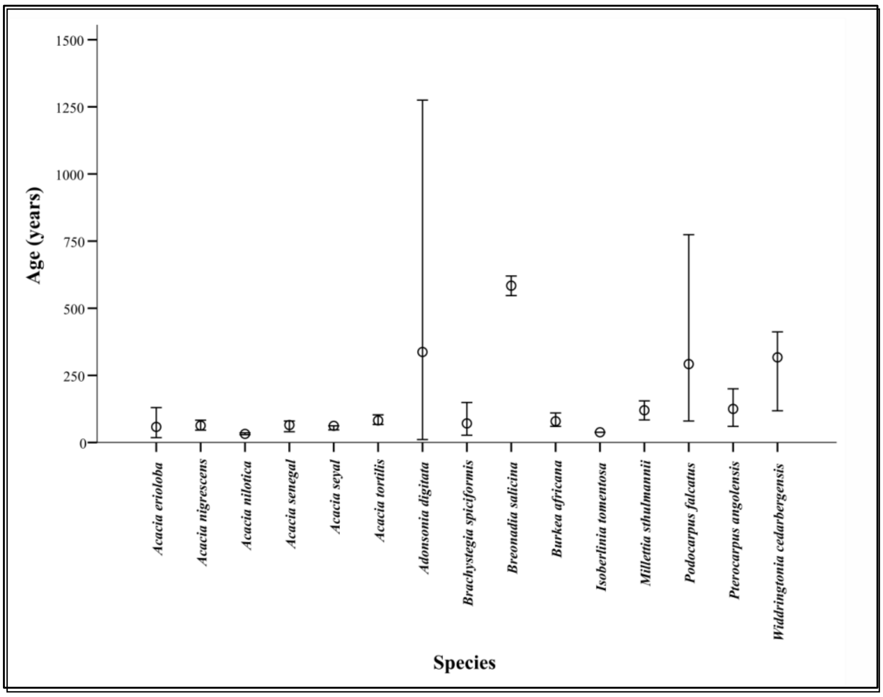

Figure 2.3: Mean, minimum and maximum recorded tree age per species

Table 2.1: Summary of dendrochronological and dendroclimatological studies ordered according to species, conducted in southern Africa (*indicates radiocarbon age determination)

Species	**Location**	**Site number**	**Min–max (mean) age (yrs)**	**Growth form issues**	**Additional analyses**	**References**
Acacia albida (L)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia burkei (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia caffra (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia erioloba (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
	Kalahari, Northern Cape, South Africa	12	18 – 139 (58); 15-210 (70)*	Decayed,wedging rings, scar tissue, termites, porous	–	Steenkamp *et al*., 2008
Acacia galpinni (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia gerrardii (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia goetzei (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia heroensis (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia karroo (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a

Species	Location	Site number	Min–max (mean) age (yrs)	Growth form issues	Additional analyses	References
Acacia nigrescens (L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
	Hluluwe–Umfolozi, KwaZulu–Natal, South Africa	11	46 – 83 (63); 68 – 75 (72)*	indistinct rings	–	February *et al*., 2006
Acacia nilotica (L.)	Hluluwe–Umfolozi, KwaZulu–Natal, South Africa	11	29 – 36 (32) 45 – 49 (47)*	indistinct rings		February *et al*., 2006
Acacia pilispina(L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia polyacantha(L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia rehmanniana(L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	Ring counts, X–ray densiometry	Gourlay, 1995a
Acacia robusta(L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia welwischii(L.)	South Africa, Zambia, Zimbabwe	1, 18, 19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Acacia xanthophloea(L.)	South Africa, Zambia, Zimbabwe	1,18,19	Undetermined	–	X–ray densiometry	Gourlay, 1995a
Adonsonia digitata(L.)	North–eastern Namibia	14	1275	Fusing of stems	–	Patrut *et al*., 2007
	Kruger National Park, Limpopo and Mpumalanga, South Africa and Skukuza, Mpumalanga	13, 9	11 – 36 (24)	Indistinct growth rings	Carbon isotopic analyses	Robertson *et al*., 2006
Brachystegia floribunda(L.)	Zambia	18	Undetermined	Missing rings	–	Syampungani *et al*., (2010)
Brachystegia spiciformis(L.)	Western Tanzania	_	25–54 (41)	Locally absent rings	–	Trouet *et al*., 2001
Brachystegia spiciformis(L.)	Western Zambia	18	27 – 57 (41)	Wedging rings	–	Trouet *et al*., 2006
	Mashonoland Province and Midlands Province, Zimbabwe	19	Undetermined	High variability of annual rings	–	Grundy, 2006
	South central Africa	_	43 – 149 (100)	Wedging rings	–	Trouet *et al*., 2010
	Zambia	18	38–50 (46)	–	Cambial growth periodicity	Trouet *et al*., 2010
Breonadia salicina(L.)	Limpopo, South Africa	1	547 – 620 (584)	Missing rings, vague annual rings, lack of samples	Carbon and oxygen isotopic analyses	Norström *et al*., 2005; 2008

Species	**Location**	**Site number**	**Min–max (mean) age (yrs)**	**Growth form issues**	**Additional analyses**	**References**
Burkea africana (L.)	Northern Namibia	16	60 – 110 (79)	Wedging rings	–	Fichtler *et al.*, 2004
Isoberlinia angolensis (L.)	Zambia	18	Undetermined	Missing rings	–	Syampungani *et al.*,2010
Isoberlinia tormentosa(L.)	Western Tanzania	_	34 – 70 (44)	Locally absent rings	–	Trouet *et al.*, 2001
Julbernadia paniculata(L.)	Zambia	18	Undetermined	Missing rings	–	Syampungani *et al.*,2010
Millettia stuhlmannii (L.)	Mozambique	26	84 – 155 (120)	Wedging and false rings	–	Remane, 2013
Mimusops caffra (L.)	KwaZulu–Natal, South Africa	10	Undetermined	–	Carbon isotopic analyses, cross–wavelet analysis	Hall *et al.*, 2009
Protea caffra (L.)	Drakensberg, KwaZulu–Natal, South Africa	10	~2400	–	–	February, 1994
Protea roupelliae	Drakensberg, KwaZulu–Natal, South Africa	10	~2400	–	–	February, 1994
Podocarpus falcatus(L.)	KwaZulu–Natal Midlands, South Africa	5	597	–		Hall, 1976
Podocarpus falcatus(L.)	Magoebaskloof, Limpopo, South Africa	6	128	Inadequately defined, locally absent and converging rings	–	Curtis *et al.*, 1978
	Witelsbos Forest, Eastern Cape	7	80 – 205 (152)	Inadequately defined, locally absent and converging rings	–	McNaughton and Tyson, 1979
	Knysna, Western Cape, South Africa	8	Undetermined	Inadequately defined, locally absent and converging rings	–	February and Stock, 1998
	Midlands,South Africa	5	774	Missing and false rings	–	Vogel *et al.*, 2001
	Eastern Cape, South Africa	27	Undetermined	–	Carbon isotopic analysis	Hall *et al.*, 2008
Podocarpus latifolius (L.)	Knysna, Western Cape, South Africa	8	Undetermined	Inadequately defined, locally absent and converging rings	–	February and Stock, 1998
Podocarpus latifolius (L.)	South Africa, Mozambique, Zambia, Zimbabwe, Botswana	1, 17, 18, 19, 26	80 – 140 (110)	Wedging rings	–	Therrell *et al.*, 2007
Podocarpus latifolius (L.)	KwaZulu–Natal, South Africa	5	Undetermined	–	Carbon isotopic analysis	Hall *et al.*, 2008

Species	**Location**	**Site number**	**Min–max (mean) age (yrs)**	**Growth form issues**	**Additional analyses**	**References**
Podocarpus latifolius (L.)	South Africa	8	Undetermined	Inadequately defined, locally absent and converging rings	–	February and Stock, 1998
Pterocarpus angolensis (L.)	Northern Namibia	16	60 – 79 (70)	Wedging rings	–	Fichtler *et al*., 2004
Pterocarpus angolensis (L.)	Zimbabwe	1,17,18,19, 26	200	–	–	Therrell *et al*., 2006
	Botswana, Mozambique, South Africa, Zambia, Zimbabwe	17, 26, 1, 18, 19	80 – 140 (110)	–	–	Therrell *et al*., 2007
	Western Zimababwe	3	120 124	Inadequately defined and discontinuous rings	–	Stahle *et al*., 1999b
Widdringtonia cedarbergensis(L.)	Cape Town, Western Cape, South Africa	3	412	–	–	Dunwiddie and LaMarche, 1980
	Cape Town, Western Cape, South Africa	3	118 – 326 (222)	–	Carbon isotopic analysis	February and Stock, 1999

2.4. Conclusion

Existing dendrochronological and dendroclimatological research in southern Africa has demonstrated the potential of tree ring series for use as palaeoclimatic proxies and scope for further research. Such research warrants increased attention in order to allow for a more comprehensive understanding of climate variation in the recent past.

CHAPTER THREE: THEORETICAL METHODOLOGY

3.1. Introduction

Dendrochronology was pioneered by Andrew E. Douglass in the early twentieth century in North America (Lilly, 1977, Hughes *et al*., 1982). His discovery of the use of tree rings as proxy climate archives was ground breaking. The development of the first long tree records eventually evolved into the field of dendroclimatology (Hughes *et al*., 1982). Responses of trees to prevailing climatic conditions are recorded in annually resolved tree growth rings, which form the basis on dendroclimatology (Hughes, 1982). The work of Douglass and his successors led to the first radiocarbon calibration using tree rings (Walker, 2005). The past few decades have seen advances in the fields of dendrochronology and dendroclimatology, such as increased citations of tree ring based reconstructions in reports by the Intergovernmental Panel on Climate Change (IPCC) (Hughes, 2002). However, much of the work has focused on the northern hemisphere, leaving a critical gap in southern hemispheric palaeoecological studies (Hughes, 1982; Trouet, 2004).

3.2. Formation of growth rings in trees

Apical growth and radial growth occur simultaneously in trees due to division of the meristem (Raven *et al*., 1986). The meristem is plant tissue that contains actively dividing cells which form new tissue. The apical meristem forms primary tissue that increases the height of the tree by extending its stems and branches (Stokes and Smiley; 1968; Raven *et al*., 1986). The lateral meristem gives rise to the vascular cambium which is the secondary tissue of the tree (Stokes and Smiley; 1968; Raven *et al*., 1986). Division of the vascular cambium leads to an increase in radial growth (Stokes and Smiley; 1968). Cell division of the vascular cambium leads to the development of secondary xylem towards the inside of the stem and secondary phloem towards the outside of the stem (Raven *et al*., 1986; Groover and Robischon, 2006). Secondary xylem is produced during the growing season of each year and accumulates as wood, resulting in the thickening of the tree stem (Groover and Robischon, 2006). Growth rings are produced by the activity of the vascular cambium during each growing season. The xylem that is laid down during each growing season appears as rings from pith to bark when viewed in cross section (Stokes and Smiley, 1968; Raven *et al*., 1986). Growth rings frequently contain both earlywood and latewood (Groover and Robischon, 2006). Earlywood is formed at the start of the growing season, during spring in temperate latitudes, and is lighter in colour (Stokes and Smiley, 1968; Groover and Robischon, 2006). This is the period of rapid radial growth (Stokes and Smiley, 1968; Groover and Robischon, 2006). Latewood is darker in colour, occurring at the end of the growing season, during summer, when cambium activity begins to decrease (Stokes and Smiley, 1968; Groover and Robischon, 2006). Rays are cells that are involved in the lateral conduction of water (Stokes and Smiley, 1968; Raven *et al*., 1986). They occur at right angles to the growth rings, appearing as horizontal bands, and can be used by dendrochronologists to aid in species identification (Stokes and Smiley, 1968).

Annual growth rings are the result of new woody stem tissue formed during a specific year (Stokes and Smiley, 1968). Variations in ring widths are due to external environmental and climatic conditions, such as temperature, precipitation, the duration of the growing season, competition for resources and disturbance events, e.g. fire (Glock, 1955; Raven *et al*., 1986). Often, the growth of a tree and the subsequent variation in ring widths from year to year are a result of the simultaneous effect of a number of environmental and climatic factors. During optimal growing conditions, such as during high precipitation, adequate temperatures and low competition for resources, tree growth is favoured, producing wider growth rings. In contrast, narrow growth rings are produced during unfavourable growing conditions. As each growth ring displays characteristic patterns, cross–dating is performed, i.e. pattern matching of growth rings from several specimens (Section 3.7.1). A calendar year is thus assigned to each growth ring and inferences on past environmental and climatic conditions can be inferred via analysis of ring widths.

As the formation of growth rings and their response to prevailing environmental and climatic conditions is controlled by several factors, a number of principles and laws have been put in place to help ensure the accuracy of dendrochronological and dendroclimatological studies (Stokes and Smiley, 1968; Lilly, 1977; Hughes, 2002).

3.3. Principles of dendrochronology

There are a number of principles that dendrochronology should adhere to, such as the law of limiting factors, the principle of site selection, the principle of sensitivity and the principle of cross–dating (Stokes and Smiley, 1968; Lilly, 1977; Hughes, 2002). The law of limiting factors states that a single factor or a group of factors should have a controlling influence on tree growth. Trees that have a limited number of controlling environmental and climatic factors are generally selected for dendrochronology (Hughes *et al.*, 1982).

The principle of site selection helps ensure that suitable trees are selected for dendrochronology. For example, arid sites are often chosen if water as a limiting factor on tree growth is being investigated. Sampling variability is fundamental to site selection (Hughes *et al.*, 1982). Larger sample sizes are required when there are larger differences within and between trees of parameters such as ring width and isotopic composition in order to provide reliable environmental and climatic reconstructions (Hughes *et al.*, 1982). Stands containing long–lived trees with relatively stable environments are most likely to provide strong climatic signals (Hughes *et al.*, 1982).

The principle of sensitivity refers to the sensitivity of growth rings to climatic conditions, i.e. the variability in thickness of the growth rings (Lilly, 1977). Trees which are very sensitive to climate correlate well with highly variable climatic conditions (Lilly, 1977).

The principle of cross–dating involves matching up patterns of ring widths within and between trees. The overlap of ring widths with each other is combined to develop a chronology that can be used to reconstruct past climates. Successful cross–dating suggests that there is a single dominant factor controlling tree growth. Cross–dating helps ensure the accuracy of tree ring series by identifying missing and false rings thereby providing a reliable representation of past climatic variations (Lilly, 1977).

Definitive growth ring boundaries are common in temperate regions where there is a distinct growing season (Lilly, 1977, Stokes and Smiley, 1968). At the end of a growing season, cambial differentiation is interrupted, altering the structural properties of xylem elements at the end of the growth ring (Lilly, 1977). These structural changes result in the formation of distinct growth ring boundaries, demarcated by boundary parenchyma (Lilly, 1977). Boundary parenchyma is produced at either the beginning or end of the growing season and is visible as white lines under the microscope (Lilly, 1977). In tropical and subtropical regions, where there is no distinct growing season, there is a lack of dormancy of the cambium layer, causing many species to produce indistinct growth ring boundaries (Stokes and Smiley, 1968). During periods of sudden increased or decreased growth, cell division either increases, decreases or stops, leading to cambial dormancy (Glock, 1955). This leads to the occurrence of missing and false rings (Glock, 1955; Stokes and Smiley, 1968).

The appearance of missing or locally absent rings, referred to as wedging rings occurs during years of limited growth (Stokes and Smiley, 1968). Radial growth is rapid in certain parts of the tree and slow or nonexistent in others, resulting in the occurrence of missing rings (Stokes and Smiley, 1968, Lilly, 1977). False rings occur when multiple growth rings are produced per year and are usually attributed to droughts and increased rainfall (Stokes and Smiley, 1968). False rings are known as multiple rings, double rings or intra–annual latewood bands (Lilly, 1977). Ring anomalies are common in dry tropical forests due to extreme climatic conditions (Trouet, 2004). False rings are common in summer rainfall areas and arid areas where there are periods of increased precipitation (Trouet, 2004).

The principle of replication is vital to cross–dating (Lilly, 1977). A larger number of samples incorporated into the cross–dating process helps increase the accuracy of cross–dating. Missing and false rings can be more easily identified in large sample sets. Non–climatic noise in samples can be reduced by averaging the ring widths of all samples, hence emphasizing the common climatic signal (Lilly, 1977).

Despite the many complications of using tree growth rings for palaeoecological analysis, there are significant advantages to the fields of dendrochronology and dendroclimatology.

3.4. Advantages

Tree rings records are continuous, widely distributed and have precise annual or higher resolution. Additionally high levels of efficiency of simple linear models to explain climate and tree ring relationships are vital for global climate change research (Hughes, 2002; Martinelli, 2004; Jones *et al.*, 2009; Gebrekirstos *et al.*, 2011). Trees are reasonably easy to sample through the collection of increment cores or stem discs (McCarroll, 2010). Due to the annual resolution provided by trees, tree rings are probably the most accurate palaeoclimate proxies for studying past climate change for the last 1000 to 2000 years (McCarroll, 2010).

Furthermore, large scale patterns of corresponding interannual variability and the increasing accessibility to tree ring chronology networks are among the advantages of using tree rings as climate proxies (Carrer and Urbinati, 2006). Trees are widespread, allowing for geographic variations of past climates to be studied, which can be more helpful for predicting future regional effects of climate change, rather than overall hemispheric or global effects (McCarroll and Loader, 2004). There is great potential to use tree rings to date other natural archives that may contain important climate information but have less precise dating, such as in dating glacial advance and retreat, annual laminations in marine sediments or ice cores (Hughes, 2002).

Long term tree ring chronologies can be used to study changes in atmospheric and sea surface temperature changes, precipitation patterns and stream flow (Trouet, 2004). Fire frequencies, insect outbreaks and air pollution can be studied using tree ring series (Trouet, 2004; von Platen, 2008). Tree ring chronologies can be used to date buildings and archaeological timbers (Bailie, 1982). The use of tree rings in sylviculture is an important application, such as providing information on tree age, growth rate and health of trees (Wimmer and Vetter, 1999). Stable isotope ratios from trees provide important climatic information, such as temperature and precipitation patterns (Leavitt and Long, 1991; Lipp *et al*., 1991; Saurer *et al*., 1997; McCarroll and Loader, 2004; McCarroll, 2010). Comparisons can be calibrated against the instrumental record, providing an accurate palaeoclimatic reconstruction (McCarroll and Loader, 2004).

The greatest strength of tree rings as a climate proxy is the potential to calibrate tree ring dates against calendar years with a very high level of certainty through cross–dating (Hughes, 2002). Due to the high accuracy of tree ring dating, tree rings can be thoroughly calibrated against calendar time scales and climate data to a degree that is unique among natural archives (Hughes, 2002; McCarroll and Loader, 2004; Jones *et al*., 2009).

3.5. Limitations

Although tree ring records provide an extensive source of annual climate data, they have several limitations (Carrer and Urbinati, 2006; Jones *et al*., 2009). For example, there is inherent bias as tree rings only contain climate data for terrestrial regions of the world (Carrer and Urbinati, 2006). Biological responses to climate change are often difficult to understand and analyse (Carrer and Urbinati, 2006). Non–climatic variability is present in tree ring series due to non–climatic disturbances and intrinsic growth patterns, which makes analyses of tree ring series exceedingly difficult (Carrer and Urbinati, 2006; Eckstein, 2007). In addition, the methods used to obtain information from tree ring series maintain select wavelengths of climate variability that may cause important data to be overlooked (Carrer and Urbinati, 2006). Standardization approaches required to remove data biases often remove important information about climate variability (Carrer and Urbinati, 2006; Jones *et al.*, 2009). As a result, few chronologies extend past the centennial time scale (Jones *et al.*, 2009).

Climate reconstructions using tree rings frequently only capture ~40–50% of the variance of the instrumental variable in question (Hughes, 2002). However, other annual climate proxies such as corals and ice cores perform more weakly than tree rings when checked against instrumental data (Hughes, 2002). Few trees respond solely to a single climate variable or equally to all variables in a season, therefore response functions are a valuable tool in deciding what variables to reconstruct (Hughes, 2002; Jones *et al.*, 2009).

As natural archives, tree rings may not record the variables desired in a study, even after careful site and species selection and response variable calculations, the best reconstructions may not be of the desired variable (Hughes, 2002). For example, a study by Fritts (1991) shows that annual temperatures on a subcontinental scale are reconstructed with great success although the species used are moisture sensitive. Moisture levels are influenced by temperature and climatic conditions associated with temperature, resulting in good temperature reconstruction. Chronologies available for the subtropics and tropics are limited, which restricts the usefulness of tree ring data in studying important climate phenomena such as monsoon circulations, which would in turn improve our understanding of global climate change (Hughes, 2002).

3.6. Methodological considerations

3.6.1. Site and species selection

Climatic information may be collected from tree rings from living or dead trees (Grissino–Mayer, 2003). Increment corers are used to extract tree cores from living trees (Grissino–Mayer, 2003). Logs, snags, remnant wood and buried or exposed sub fossil wood are other archives of tree rings (Grissino–Mayer, 2003). Timber from historic buildings can be sampled to add to the tree ring record when dead or living trees are unavailable (Grissino–Mayer, 2003).

Dendrochronologists select species and sites based largely on the predominant species that is present in a particular site, which is most likely to provide a climatic signal (Grissino–Mayer, 2003). For example, previous studies have shown that *Podocarpus* lacks growth rings and will therefore provide a weak climatic signal as opposed to *Pinus* which studies have shown provide a stronger climatic signal than *Podocarpus* (Grissino–Mayer, 2003). In a region where both species exist, dendrochronologists are therefore more likely to sample *Pinus* (Grissino–Mayer, 2003). In some studies, all species present in a region need to be sampled, for example, studies that require a representation of forest age structure (Grissino–Mayer, 2003).

Tree species unsuitable for use in dendroclimatology include those species that are not long lived, have poor growth ring structure and trees that are scarce (Lilly, 1977; Hughes *et al*., 1982). Life expectancy is an important consideration when selecting species to work with (Lilly, 1977). Dendrochronological records need to be extended back as far as possible, requiring long lived trees. Tree size, girth and height can be used as a basis for assessment when determining longevity of trees (Lilly, 1977; Hughes *et al*., 1982).

3.6.2. Field techniques

3.6.2.1. Increment cores

Swedish increment corers are precision tools used to collect tree cores for dendrochronological analyses (Stokes and Smiley, 1968; Bailie, 1982; Grissino–Mayer, 2003). Increment corers were designed for use on softwood trees (Bailie, 1982). The majority of sampling outside of the tropics is conducted using increment corers. The increment corer removes a core from a living tree with minimal damage to the tree (Stokes and Smiley, 1968). Holes left in the tree after the extraction of the core are sealed by sap, preventing parasites from entering the tree and causing harm (Stokes and Smiley, 1968). Increment cores are generally taken at breast height from the pith of the tree (Therrell *et al*., 2007). Coring of hardwoods requires a high level of physical strength and extra care needs to be taken to ensure that the auger of the corer does not become damaged or break during use (Grissino–Mayer, 2003).

3.6.2.2. Stem discs

Stem discs may be extracted from living or dead trees via a chain saw (Grissino–Mayer, 2003). Stem discs are taken above ground level (Therrell *et al*., 2007). Due to the increased occurrence of missing, wedging and indistinct rings in trees from southern Africa, stem discs are more suitable for tree ring analysis than cores (Lilly, 1977; February, 2000). Multiple radii can be analysed on stem discs, allowing for more accurate tree ring counts and climate reconstructions (Fichtler *et al*., 2004; Trouet *et al*., 2006). Unfortunately, trees need to be felled for the collection of stem discs, destroying the tree (Trouet, 2004). However, stem discs can be collected from fallen or dead trees (Patrut *et al.*, 2007). Permission is often needed for the collection of full stem discs from forests and nature reserves.

3.6.2.3. Data interpretation

Chronologies developed near the limits of a species' ecological range generally react to a single climatic factor, unlike individuals closer to the centre of its ecological range where climate responses may be more complicated (Hughes, 2002). Species from high elevations or high latitudes without considerable moisture stress show a linear relationship with surface temperature during the growing season (Hughes, 2002). The response of tree rings to climate is controlled by conditions during the growing season and by the climate during a specific part of the year that has most strongly influenced the trees immediate functioning environment (Lilly, 1977; Hughes, 2002). Therefore climate reconstructions may be based on studies that have used sites with similar ecological and climatic conditions so that the same climate variable is recorded. Alternatively studies are based on a number of sites that have varying ecological and climatic conditions, thereby reconstructing climate using a number of climate variables (Hughes, 2002).

3.7. Standardisation

As trees grow, there is an associated decrease in radial growth over time, i.e. the radial growth of younger trees is much faster than that of older trees, resulting in heteroscedastic variance in multiple tree ring series (Cook, 1985; Cook and Peters, 1997). Standardisation or indexation removes non-climatic variations from tree ring series', leaving only the climatic variation common to all trees (Cook, 1985; Helama *et al*., 2004). A standardised tree ring series therefore represents the amount of radial growth produced each year by a tree if all climatically associated growth influences stayed constant over time (Cook, 1985; Cook and Peters, 1997). Several standardised tree ring series can therefore be averaged together to produce a master chronology that is suitable to study past climate changes (Cook, 1985; Cook and Peters, 1997).

Simple, stochastic trend removal fits the observed ring widths rather than theoretically estimated ring widths. Simple linear regressions, modified exponential curves, digital filtering and orthogonal polynomials are the most commonly used methods in dendrochronology to standardise tree ring series (Cook and Peters, 1981; Cook, 1985; Helama *et al*., 2004). According to Cook and Peters (1981), the cubic smoothing spline is an orthogonal polynomial approach that is well suited for standardisation of tree ring widths. This method is well suited for dendrochronology as the spline is highly adaptable and can be applied to a variety of age related growth trends found in tree ring series.

Once the trend has been identified in the tree ring series, the trend needs to be removed to complete the standardisation process. The trend is removed by either subtracting the value of the trend line from the data. This will result in a time series of residuals from the trend. The residual series uses the same units as the original time series. Alternatively, the ratio of every the tree ring series to the trend line is calculated for every point. The ratio will be larger than 1.0 when the time series is above the trend line and will be below 1.0 when the time series is below the trend line. Each ring width series is reduced to a series of dimensionless indices and a homoscedastic variance (Cook, 1985). Both trend removal methods are used in dendrochronology. However, it should be noted that the ratio method should not be used if the time series consists of negative values. Standardization techniques may result in biased chronology values (Helama *et al.*, 2004). Important information may be removed through standardisation leading to the underestimation of the climate's natural variability. This causes incorrect determinations of climate change (Helama *et al.*, 2004). Carefully made considerations based on available tree ring data and the purposes of each study are therefore important when deciding whether to detrend tree ring series using standardisation techniques and if so, on choosing a suitable standardisation technique (Rinn, 2012).

3.8. Chronological tree ring dating

3.8.1. Cross–dating

Cross–dating is a technique in dendrochronology used to accurately date growth rings and relies on the basics of dendrochronology that each annual tree ring is dated according to the year that it was formed (Stokes and Smiley, 1968; February *et al.*, 1998). The aim of cross–dating is to assess year to year agreement within and between patterns in ring widths (Stokes and Smiley, 1968). The inward rings, closest to the pith, may also be dated according to the accurately dated outermost ring, those rings closest to the bark (February *et al.*, 1998). Cross–dating is not a simplistic procedure due to the possibility of missing or false rings (Stokes and Smiley, 1968). In addition, measurement errors may result in the incorrect identification of ring boundaries (Stokes and Smiley, 1968). Other factors further compound cross–dating such as complete annual growth failure due to droughts, fires or insect defoliation which may occur in some samples and not others from the same stand (von Platen, 2008). Using disturbance events as marker years during cross–dating should be performed with caution as there is an increase in the likelihood of false and missing rings due to the stressful effects of disturbances on tree growth (von Platen, 2008). Trees younger than five years old should not be used for cross–dating as young trees have different physiological responses to climatic factors compared with mature trees (Worbes, 2002). Successful cross–dating between individual trees and between trees from several sites indicates that growth rings are annual in nature (Stahle, 1999b). According to Pilcher (1990), successfully cross dated time series should reach a minimum of 40 years. Successful cross–dating indicates the influence of external factors on tree growth, such as climate (Stahle, 1999a, b; Trouet, 2004; 2006).

Cross–dating is done both visually and statistically (Fichtler *et al*., 2004, Trouet, 2004, Trouet *et al*., 2006; von Platen, 2008). Visual cross–dating involves plotting measured ring series as graphs and comparing these graphs against each other. Notes are made on the graphs at the position of any problematic rings, allowing errors to be checked and corrected by referring back to the samples. One such method that is considered highly accurate is the skeleton plot method (Stokes and Smiley, 1968).

A skeleton plot is a graphical means of representing tree ring series on graph paper (Stokes and Smiley, 1968). Tree ring series are plotted on graph paper beginning with the innermost ring. Each vertical line of the graph paper represents one growth ring and its width. Longer drawn lines represent narrower rings. The width of each ring is also scored a value between 1–10, with narrower rings having values closer to ten. However, rings width average widths are not scored and wider rings are marked with the letter ‘B’. Widths of growth rings are plotted in relation to the surrounding three to five rings. Therefore it is important to note that relative ring width rather than actual ring width is considered when using the skeleton plot method. Decades are noted on the skeleton plot by using a single dot on every tenth ring, two dots on every 50th ring and three dots on every 100th ring.

Following skeleton plotting of each sample, several skeleton plots are compared with one another. Patterns in ring width variations are visually matched up within and between samples, i.e. cross–dating, and missing and false rings are detected, to produce a composite skeleton plot (Stokes and Smiley, 1968). The composite skeleton plot represents the pattern of wide and narrow rings common to all samples and thus finds the time period common amongst samples. If patterns of ring widths cannot be matched against each other, then cross–dating is unsuccessful. A successful composite plot dates each sample relative to each other. Calendar dates are then assigned to each growth ring by comparing the composite skeleton plot with a previously dated master chronology.

Although visual cross–dating is a subjective method, it is widely practised, especially when used in conjunction with statistical analyses (von Platen, 2008). Statistical cross–dating procedures are done using specialized software such as TSAP and Cofecha. Statistical analyses are used to quantify the accuracy of visual cross–dating (Trouet, 2004; von Platen, 2008).

Bailie and Pilcher (1973) developed a cross–correlation algorithm to calculate Student's t values for all positions of overlap of two series:

$$t = \mathrm{r}\frac{\sqrt{\mathrm{n}-2}}{\sqrt{1-\mathrm{r}^2}} \tag{3.1}$$

where n = number of values, r = correlation coefficient

t–values indicate the degree of similarity of two time series while taking into consideration the number of observations (Bailie and Pilcher, 1973). t–values are calculated for all positions of overlap between series thereby providing an estimate of the accuracy of cross correlation between series (Trouet *et al*., 2006). According to the t–distribution, t–values that exceed 1.96 are significant at the 0.05 level and t–values that exceed 2.55 are significant at the 0.01 level. However, in dendrochronology, t–values must exceed 3.5 to be considered significant where $p<0.0001$ (Trouet, 2004).

Additionally, the Gleichläufigkeitskoeffizient (GLK) is used to investigate whether cross–dating is successful. GLK is a nonparametric statistical method for analysis of concordance that analyses year to year similarity between interval trends of two chronologies (Fichtler *et al*., 2004; Trouet *et al*., 2006). GLK was developed specifically for dendrochronological analyses and is based on the sign of agreement between the two chronologies, expressed by the following equation:

$$\Delta_i < 0 : \; G_{ix} = -\frac{1}{2}$$

$\Delta_i = x_{i+1} - x_i$ when $\Delta_i = 0 : G_{ix} = 0$

$$\Delta_i < 0 : \; G_{ix} = -\frac{1}{2}$$

for two curves x and y

$$G_{(x,y)} = \frac{1}{n-1} \sum_{i-1}^{n-1} \lfloor G_{ix} + G_{iy} \rfloor \tag{3.2}$$

where, G = Gleichläufigkeit, n= number of values, x,y = time series, Δ_i = difference in tree ring width between two consecutive years

Successful cross–dating is signified by a GLK value greater than 70%, indicating that 70% of either the increasing or decreasing slopes between two series are equal (Trouet, 2004). By combining both the t–test and GLK test, statistical cross–dating is optimised (Trouet, 2004).

Following Trouet (2004), the threshold used in this research for two series to be cross–dateable was set at t=2 for correlation analysis and GLK=60%, which is significantly lower than the thresholds set in dendrochronology for temperate regions. The thresholds for tropical regions can be significantly lowered as no reference chronology is available for the tropics, resulting in tree series being compared against each other as opposed to a reference chronology during cross–dating (Trouet, 2004). Another justification for the lower thresholds is that the trees are of known cutting date, so an approximate date of the youngest measured ring is available. The range of possible dates is therefore limited, allowing for the thresholds applied being lowered (Trouet, 2004). If a single date within a tree ring series has distinctly higher t and GLK values, than the other dates, that date is considered correct (Trouet, 2004).

The cross–date index (CDI) calculates a date index of potential series matches and uses both the GLK and t–values to assess the quality of the match, with the highest assessment being CDI=1.00 (von Platen, 2008). The CDI formula is calculated as follows:

$$CDI = \left(G - 50 + 50\frac{\sqrt{overlap}}{\max overlap}\right) \times T$$

(3.3)

where G = GLK+_SGLK + S_GLK + SSGLK $\div n$ where n = number of operators in the numerator

$$\mathrm{T = TVBP + TVH \div 2}$$

(3.4)

TVBH and TVH are used in TSAP–Win (Rinn, 2012) to detrend or transform ring width data before calculating the t–statistic so that the distribution is normalised. Signatures are used to weight the GLK value as signatures show the number of increasing and decreasing members derived from the source series (von Platen, 2008). This results in the signature GLK factor (SGLK). _SGLK, S_GLK and SSGLK represent signature years located in measurement series calculated by:

SGLK= $\sum(yi_j = x_{ij})$ and is provided in %

(3.5)

where SGLK = signature GLK −% sum of equal slope intervals (refers specifically to chronology signature years), _SGLK =standard signature GLK where sample is the sample series and reference is the chronology, S_GLK = signature – standard GLK where sample is the chronology and reference is the sample series, SSGLK = signature – signature GLK where both sample and reference are the chronology (von Platen, 2008).

Growth rings often exhibit variations in width attributed to climatic factors which forms the basis for cross–dating among samples from the same study site or region (February *et al.*, 1998; Gutsell and Johnson, 2002; Martinelli, 2004; Gebrekirstos *et al.*, 2011). Signal years with high inconsistencies in ring width are matched up within and between trees to confirm original dating (February *et al.*, 1998). Signal years can be used as markers to identify regional events such as fires or droughts (von Platen, 2008). Different events produce different signals in tree ring chronologies (von Platen, 2008). For example, wide annual rings are more prevalent after a fire due to reduced competition and increased nutrient availability while very thin, narrow rings may indicate stressful growing conditions such as a drought (von Palen, 2008). It is possible to misinterpret events with similar signals. For example, insect defoliation can result in narrow growth rings. Where droughts and defoliation occur concurrently, errors in the interpretation of tree ring series can occur (von Palen, 2008). Following successful cross–dating, standardisation is applied to tree ring series to remove long term growth trends from the series (Trouet, 2004; von Palen, 2008).

3.9. Characterisation of tree ring chronologies

There are several parameters used for the characterisation and comparison of tree ring chronologies. Tree ring chronologies are characterized by the number of samples used and the age ranges of the samples. Trouet (2004) states that the age of a chronology is based on the minimum age of at least four individual trees. Mean values, standard deviations, sensitivity and correlation coefficients are used to characterize tree ring values. Mean values and standard deviations of tree ring series are calculated using raw data (Trouet, 2004). Mean refers to the average value of a dataset while standard deviation is a measurement of the dispersal of data from its mean. According to Schweingruber (1988), mean values of single series reflect ecological conditions affecting a sample site. Standard deviation measures ecological homogeneity of a site and increases with increasing heterogeneity of a sample site (Trouet, 2004).

Tree sensitivity to climatic factors can be calculated through mean sensitivity values, following Schweingruber (1988):

$$\bar{S} = \sum_{i=1}^{n-1} |S_i + \ 1| \, n - 1 \quad \text{with} \qquad S_i = \frac{(x_i + x_{i-1}) \, . \ 2}{(x_i + x_{i-1})} \tag{3.6}$$

where x_i = the observed number of values of tree ring series x at moment i, n = the number of observations, i.e. number of rings in a series, S_i= the sensitivity in time interval i

Mean sensitivity values are a measure of between ring variability, with higher values indicating higher sensitivity to climatic factors. This implies a stronger limitation on tree growth by climatic factors (Lilly, 1977).

Pearson’s autocorrelation measures similarity within a time series with a time displacement of one or more years (Trouet, 2004). The Pearson’s autocorrelation coefficient measures the sensitivity of tree growth in a given year to growth in the previous year (Trouet, 2004). The following calculation is used to calculate Pearson’s autocorrelation coefficient for data with a normalized distribution:

$$r = \pm \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \tag{3.7}$$

with x = ring width for year i, y = ring width for year i, $\bar{x}$ = mean ring widths in series, $\bar{y}$ = mean ring widths in series

The Spearman Rank is used instead of Pearson’s autocorrelation to test data that does not have a normal distribution:

$$r = 1 - \frac{\sigma \sum d^2}{n^3 \ - n} \tag{3.8}$$

with d = difference in rank between ring widths, n = total number of ring widths

Long term variations in growth curves of raw data must be removed prior to calculation of the autocorrelation coefficient so that correlations such as age trends between series can be eliminated (Trouet, 2004). For that reason, standardised data is used when calculating autocorrelation coefficients (Trouet, 2004). The percentage of variation explained through the first eigenvector of the correlation matrix of the indexed tree ring series over a common time period assesses the common variation between all the time series (Trouet, 2004).

3.10. Time series analysis

3.10.1. Correlation analysis

Correlation analysis assumes a linear relationship between two variables with no assumption of causality. As Pearson’s correlation coefficients are measures of the variation common in two datasets and are affected by trends in the datasets, these trends need to be removed prior to calculation of the correlation coefficients (Trouet, 2004). Correlation functions in dendroclimatology consist of a series of correlation coefficients between a tree ring chronology and each climatic variable (Trouet, 2004). The significance level when conducting multiple correlations is 0.05. Bonferroni adjustments for multiple comparisons are used to safeguard against increased error rates, i.e. Type II error (Trouet, 2004). Type I errors occur when a null hypothesis is rejected when it is true, i.e. a correlation between variables exists but is not detected. Type II errors occur when a null hypothesis is accepted when it is false, i.e. a correlation between variables does not exist but is detected. Following Trouet (2004), Bonferroni corrections were not applied during this research since null hypotheses were not explicitly tested. Instead probable physiological and biological causes were considered during the interpretation of correlation results of tree growth with climate.

3.11. Conclusion

This chapter has described the applications, advantages and limitations of tree ring analysis in detail. Field techniques and site and species considerations were discussed in detail so as to inform field work, i.e. site and species selection and data collection. The theoretical backgrounds of time series analysis were provided. Methodological considerations for each method were addressed such that the specific methods that were used in this research were chosen based on the theoretical considerations presented in this chapter.

CHAPTER FOUR: MATERIALS AND METHODS

4.1. Site description

Bonamanzi Game Reserve (BGR) is a 4000 ha reserve located in Zululand, northern KwaZulu-Natal. The reserve is bordered by iSimangaliso Wetland Park and Hluhluwe River, which forms part of a UNESCO World Heritage Site, declared in 1999 (Carbutt and Goodman, 2013). BGR is situated at 28º4’S and 32º19’E with an altitude of 39 m above sea level (Figure 4.2). The reserve has a tropical climate with relativity high humidity and high annual temperatures (van Heerden and Wingfield, 2002). The mean annual temperature is 18.5 ºC with January and September being the warmest and coldest months respectively (Skowno *et al*., 1999; Figure 4.1). Hluhluwe receives on average 590 mm of rainfall per year, predominantly during summer months, i.e. October to March (Skowno *et al*., 1999; Figure 4.1). There is a distinct cyclical rainfall pattern with wet and dry periods of ten years respectively (Bate and Taylor, 2008).

Northern KwaZulu-Natal is classified as savanna biome with distinctive grassy ground layer and an upper woody layer of vegetation (Mucina and Rutherford, 2006). Grass dominance in the savanna biome is maintained by summer rainfall and the lack of sufficient annual rainfall needed for the establishment and dominance of large trees (Mucina and Rutherford, 2006). Acocks (1988) classified the main veld types in the Zululand region as Zululand Palm Veld, Zululand Thornveld, and Bushveld.

Vegetation in BGR ranges from *Acacia*–dominated savannas to open grasslands, thickets and bushveld (Acocks, 1988; Bond *et al*., 2001). There are several bioregions present in the reserve including sand forest, tropical forest, coastal grassland and woodland. BGR has a diverse range of mammal species including Nyala, elephant, rhino, giraffe and red duiker. The reserve has over 408 recorded bird species.

BGR was established on agricultural land which was previously used for cotton fields, sugarcane and cattle grazing, before being converted to a reserve. The invasive plant *Chromolaena odorata* is well established in the reserve. Due to damage to natural vegetation caused by *Chromolaena*, management practises of BGR are generally to remove the plant from the area, either mechanically or chemically. Densely invaded areas in BGR are mulched using a mulcher to remove all the *Chromolaena* plants from the area (Greenland, 2012). In addition, BGR management considers *A. nilotica* to be of an invasive nature in the park. Mulchers are a cost effective method of removing invasive plants from an area with little disturbance caused to the soil (Greenland, 2012). However, all vegetation in that area is removed, along with the invasive plants. The *Acacia* savanna in BGR was highly invaded with *Chromolaena* and management plans were to mulch the area, which would have led to the demolishment of all the *A. nilotica* trees in that area. Before mulching could take place permission from BGR management was granted for the collection of *A. nilotica* trees for use in this research.

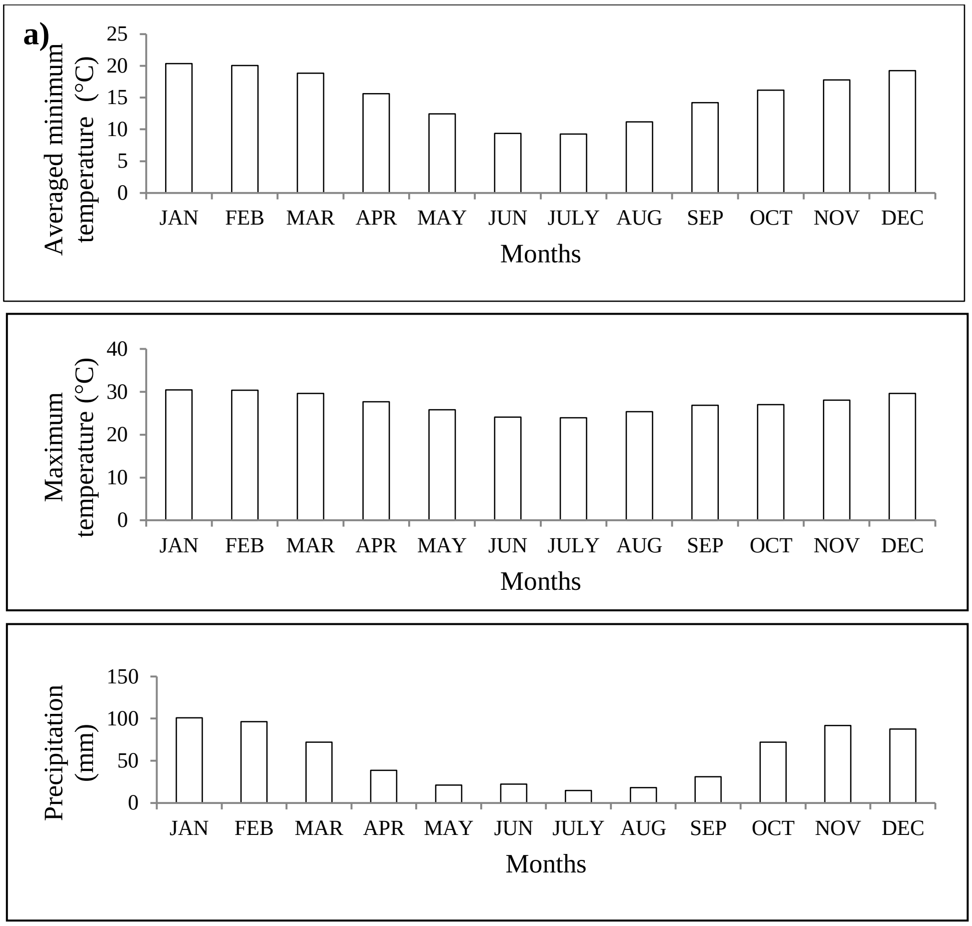

Figure 4.1: Regionally averaged local climate variables (South African Weather Service) for BGR including (a) minimum temperature; (b) maximum temperature; and (c) precipitation for the time period 1982–2012.

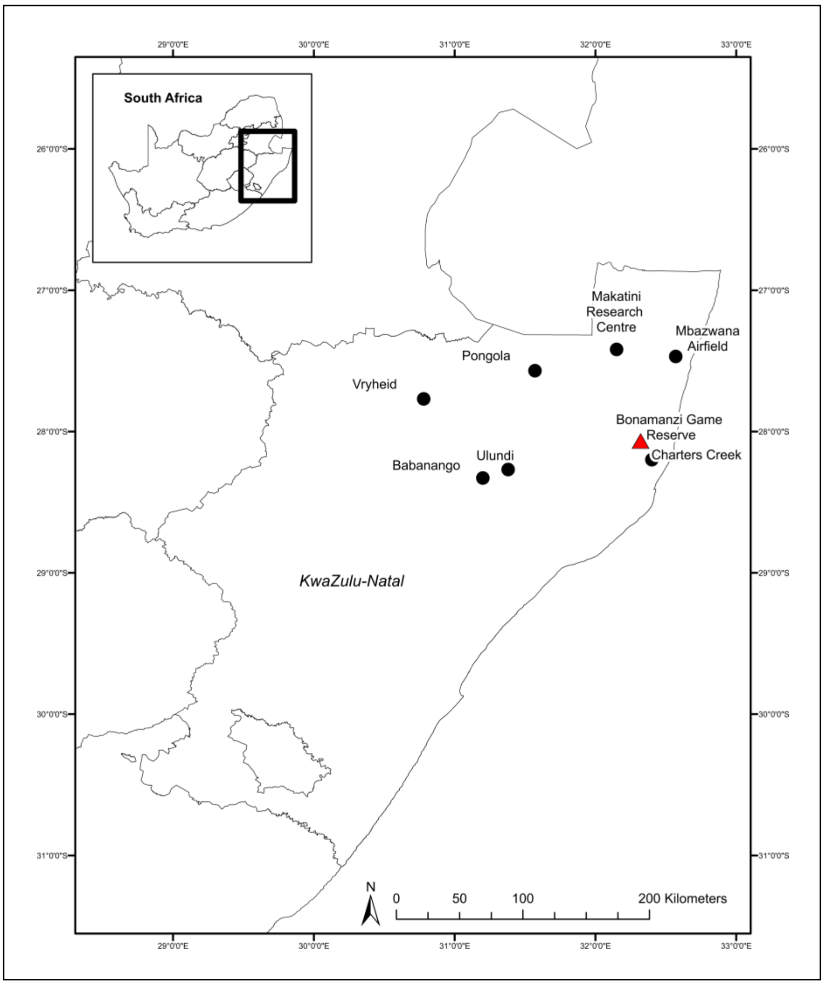

Figure 4.2: Location of Bonamanzi Game Reserve and surrounding weather stations in KwaZulu–Natal, South Africa

4.2. Field techniques

4.2.1. Pilot field reconnaissance

An initial sampling effort was conducted in August 2012. Attempts of core collection were not possible as the corers either broke or were damaged. Stem discs would be preferable for analysis rather than cores, due to the possible presence of wedging, missing and false rings, which only further complicate analyses on cores (Trouet *et al*., 2006). Stem disc collection by felling of *A. nilotica* using a hand saw proved to be impractical due to the thickness and density of the wood. The strength required to manually fell a single *A. nilotica* tree proved to be immense and therefore impractical.

4.2.2 Collection of samples

Thirty two *A. nilotica* trees were sampled at BGR during April 2013. Trees were felled after the rainy season. Thirty two samples were selected based on diameter at breast height, ranging between 300 to 1020 mm. Samples belonged to the same geographic locality so as to control for local conditions that may impact growth, such as topography and soil conditions. As trees belonged to the same geographic locality, trees were influenced by similar climatic conditions. Trees sampled also consisted of a broad age range, ranging from juveniles to mature adults. GPS co-ordinates were recorded. Measurements taken for each tree prior to felling included tree height (m) and diameter at breast height (cm). Sample measurements taken included sample height (cm) and diameter at sample height (cm) (Plate 4.1). The trees were felled using a chain saw (Plate 4.1). Tree 31 was felled but the sample was not collected due to severe rot. Two to four stem discs were collected from each of the thirty one sampled trees, yielding a total of 92 discs. Discs were collected depending on the quality of the sample in terms of the cleanness of the cut. Higher repetitions of discs were collected from samples with poorer quality compared with samples of higher quality, i.e. discs with poorer quality were discs that were unevenly cut. Each tree was felled at the thickest part of the trunk to ensure that maximum growth was accounted for, thus the height and width of each sample varied. Sample height varied between 2 to 5.5 m. Sample widths varied between 300 to 1020 mm. Discs were wrapped in newspaper to absorb moisture, labelled and packed in crates for storage and transport back to the laboratory.

Plate 4.1: a) Field measurements of *A. nilotica* being taken b) Felling of *A. nilotica* using a chainsaw

4.3. Laboratory analyses

4.3.1. Preparation of stem discs

Once at the laboratory, samples were allowed to air dry at room temperature for approximately four weeks. Samples were wrapped in fresh absorbent paper at regular intervals to absorb sap. Stem discs were polished using progressively finer sandpaper to achieve a high shine finish so as to increase visibility of growth rings, thereby facilitating microscopy. Polishing began using a bench mounted belt sander with 60 grain sandpaper followed by 120 grain sandpaper. One face per disc was sanded. The polish of the discs were assessed under the microscope and it was determined that further sanding was required, in order to achieve a smoother finish to better assess the growth rings. A handheld electric sander was used to polish the discs with grains of sandpaper ranging progressively from 40 to 600 grain (40, 100, 180, 240, 320, 400 and 600 grain).

4.3.2. Age determination

4.3.2.1. GIS mapping

Aerial photographs and satellite imagery acquired from National Geo–Spatial Information South Africa were used to determine tree establishment dates in BGR, as a form of independent chronological control. This was performed using GPS co–ordinates and georeferencing against aerial photographs for the years 1937, 1960, 1969, 1990, 2001 and satellite imagery from 2009 using ArcMap (v9.3, ESRI 2008).

4.3.2.2. Growth ring analysis

One disc per tree with the highest sample quality based on ring visibility was selected and analysed under a low resolution (0.5 X) Leica® M50 stereo microscope attached to a LINTAB 6 measurement table (Rinntech, 2012). According to February *et al.* (2006), two overlapping parenchyma bands in *A. nilotica* represent one year of growth. This study therefore assumed that growth rings present in *A. nilotica* were annual in nature. Growth rings were traced across the disc for each stem disc to ensure that false rings were not counted. Growth rings were counted and ring widths were simultaneously measured under the microscope along two to four radii per sample with close attention paid to the occurrence of wedging, missing or false rings. The number of radii counted depended on the sample quality. Samples where growth rings were not easily identified required counting along multiple radii, i.e. greater than two radii, to increase accuracy. Radii were drawn on stem discs using standard HB pencils for visibility. Rings were counted from pith to the bark and perpendicularly to growth rays along a reticule to improve accuracy and were readjusted when necessary, i.e. growth rays must always be perpendicular to growth rings to increase accuracy of ring counts (Fichtler *et al.*, 2004). Measurements were done to the closest 0.001 mm ensuring a high level of precision. Age-diameter relationships and growth rates (mean annual diameter increment) of *A. nilotica* were determined by dividing tree diameter by tree age (Therrell *et al.*, 2007).

4.3.2.3. Standardisation and Cross–dating

Pre–trend removal and standardisation were performed on growth curves so as to remove long term growth trends from individual curves by division of a one-sided running mean of five years using TSAP software (Fichtler *et al.*, 2004; Trouet, 2004; Trouet *et al.*, 2006; (Rinntech, 2012). This method of standardisation was chosen as it yielded the smallest standard deviation and variance. This resulted in the transformation of the time series into indexed curves.

Patterns of variation in ring width between trees were analysed via cross–dating. Cross–dating was performed within trees and between trees. Following visual comparison of the ring width series, statistical analyses were used for verification of cross–dating results using TSAP software (Rinntech, 2012). Firstly, cross–dating was performed within trees, i.e. radii from the same sample were cross–dated against each other. Student's t-test, GLK and CDI were the main parameters used to measure the success of cross–dating between trees and within trees (equations 3.1; 3.2; 3.3). Samples that yielded t–values ≥ 2 ($p<0.0001$) and GLK values ≥ 60, when referenced against one another, were used to develop a master chronology. CDI values that were higher were considered more reliable (von Platen, 2008).Mean growth curves for each individual tree were produced by averaging the cross-dated indexed curves for each tree. Cross–dating between trees was performed using the indexed average growth curves of individual trees. As no relevant reference chronology exists for South Africa, trees were cross-dated against one another so that a reliable index chronology could be developed (Fichtler *et al.*, 2004; Trouet *et al.*, 2006). According to Schweingruber (1988), a minimum of 12 trees should be used to ensure accurate cross–dating, thus the development of an accurate chronology. Trees that were successfully cross-dated were combined to create a mean site chronology. Additional thresholds used were GLK$\geq$60 and t-value$\geq$2 ($p<0.0001$). Descriptive statistics, such as mean sensitivity and autocorrelation of the master chronology were calculated using TSAP software (equations 3.6; 3.7).

4.3.3. Correlation analysis

4.3.3.1. Weather station data with master chronology

Annual climate data, i.e. minimum and maximum monthly temperatures and monthly precipitation data, obtained from the South African Weather Service (SAWS) were used for correlation analysis with the tree ring data (Table 4.1). The variables selected are the most common analysed in tree ring studies (Hall, 1976; McNaughton and Tyson, 1979; Dunwiddie and LaMarche, 1980; Gourlay, 1995; Trouet *et al*., 2001; Fichtler *et al.,* 2004; Therrell *et al*., 2006; Trouet *et al*., 2006). The climatic dataset consisted of rainfall and temperature records from seven weather stations located in the vicinity of BGR (Figures 4.1: 4.3).

Table 4.1: Time span of climatic variables available for weather stations situated around BGR

Weather station	Time span of available minimum and maximum temperature and precipitation records
Babanango	1996—2012
Charters Creek	1993—2012
Makatini Research Centre	1982—2012
Mbazwana Airfield	1997—2012
Pongola	1990—2012
Ulundi	1997—2012
Vryheid	1992—2012

Monthly and annual temperature and precipitation data were averaged for all seven weather stations over all common periods (1981–2012). Complete data was provided by SAWS until December 2012. Regionally averaged precipitation data provide more reliable results than single station data (Blasing *et al*., 1981). Furthermore, the statistical relationships between tree growth and climatic data may be improved by using averaged climate data (Blasing *et al*., 1981; Trouet *et al*., 2006). Averaged climate data are more likely to reveal dendroclimatic relationships that may be hidden by specific characteristics of a single weather station, particularly in summer rainfall climates (Blasing *et al*., 1981).

Correlation analysis was used to help interpret tree growth responses to climatic conditions for both monthly and annual climatic data using SPSS software (IBM SPSS Statistics, Version 21). Each climatic variable, i.e. minimum temperature, maximum temperature and precipitation was correlated separately with the master chronology. Pearson's correlation coefficient was used with a 5% significance level. In the case of climatic variables that were not normally distributed, Spearman's Rank was used with a 5% significance level. Correlation analyses between tree growth and climatic variables were compared during the growing year (October to September), during the rainy season (October to March) and the total sum of each variable.

4.3.3.2. Climate indices with master chronology

As local climate data only covered the last 21 years of the master chronology, regional climate correlations were further investigated using the KNMI Climate Explorer database (Trouet and van Oldenborgh, 2013; www.climexp.knmi.nl). The CRU TS3.2 dataset of monthly 1.0° gridded fields was chosen for analysis with the master chronology due to its spatial and temporal extent, i.e. global coverage between 1901–2009 (Figure 4.3) (Harris *et al*., 2013). The grid points used covered the extent of BGR. Additionally the response of growth of *A. nilotica* to the Southern Oscillation Index (SOI) and El Niño 3.4 index, which are both indices of the El Niño Southern Oscillation (ENSO) phenomenon were investigated using CRU index data (Figure 4.3) (Ropelewski and Jones, 1987; Kaplan *et al*., 1998). Correlation analyses between tree growth and climate indices were compared during the growing year (October to September) and during the rainy season (October to March). ENSO indices were additionally compared to the period of December of the previous year to May of the current year, as this is when ENSO phenomena is the strongest in southern Africa (Fichtler *et al*., 2004; Trouet *et al*., 2010).

ENSO represents annular variations in sea surface temperatures, air pressure, convective rainfall and atmospheric circulation over the equatorial Pacific Ocean (Ropelewski and Jones, 1987; Kaplan *et al*., 1998). ENSO is considered to be a primary determinant of rainfall at low latitudes, such as southern Africa (Nicholson and Kim, 1997). El Niño refers to the periodic warming of sea surface temperatures due to ocean–atmospheric interactions, across the central and eastern Pacific Ocean. La Niña refers to the periodic cooling of sea surface temperatures across the central and eastern Pacific Ocean, due to the ocean–atmospheric interactions. South Africa receives higher than average rainfall during La Niña conditions and is the positive phase of the ENSO cycle. Lower than average rainfall and dry conditions occur during the negative El Niño phase of the ENSO cycle.

The CRU SOI data covers the period between 1866–2006 and are an indication of the strength of sea surface temperature differences of El Niño and La Niña between Darwin and Tahiti (Ropelewski and Jones, 1987). SOI measures ENSO activity with negative SOI values corresponding to the El Niño phase of ENSO, due to low surface air pressure at Tahiti and high surface air pressure at Darwin. Conversely, positive SOI values corresponding to the La Niña phase of ENSO are attributed to high surface air pressure at Tahiti and low surface air pressure at Darwin (Ropelewski and Jones, 1987). The CRU El Niño3.4 index covers the period between 1856–2013 and is considered the best indicator of the strength of El Niño and La Niña (Kaplan *et al.*, 1998)

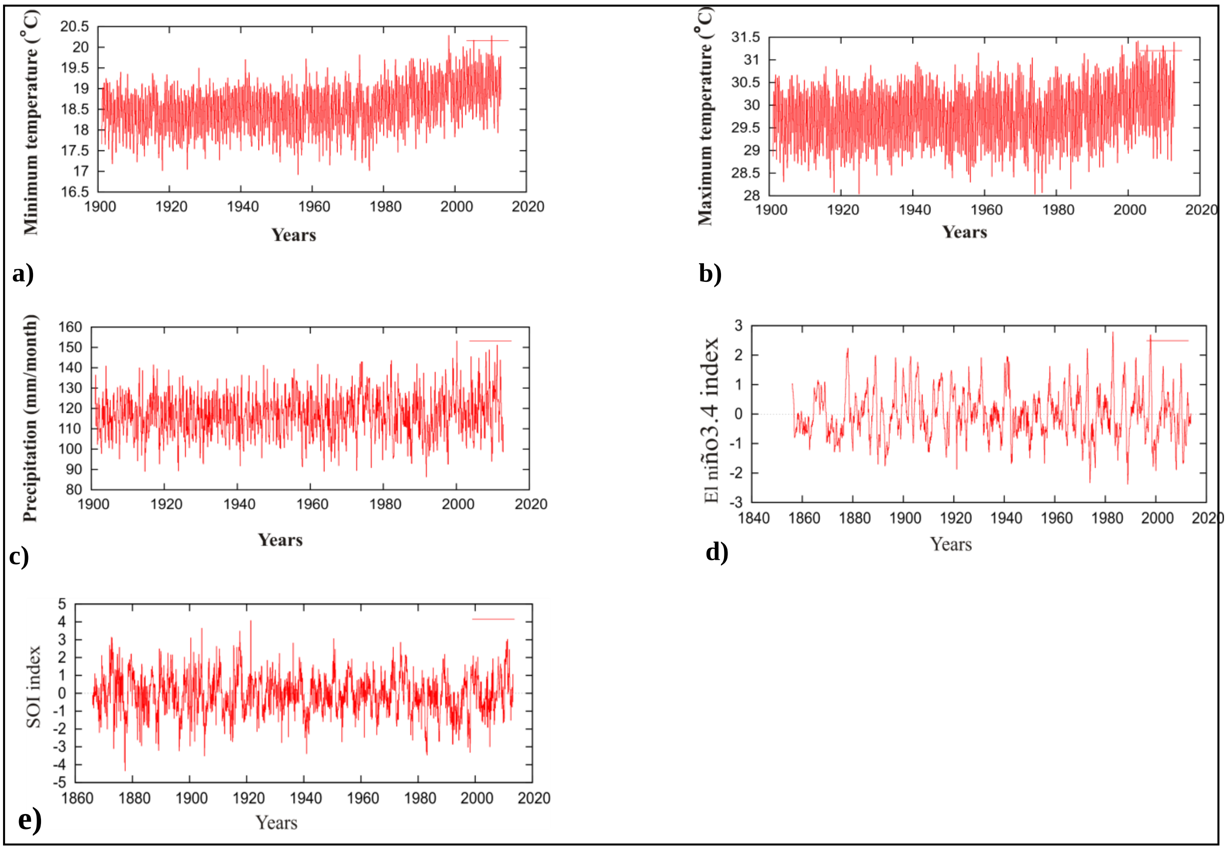

Figure 4.3.a) Minimum temperature index for BGR for the period 1901–2009 (after Harris *et al.*, 2013) b) Maximum temperature index for BGR for the period 1901–2009 (after Harris *et al.*, 2013) c) Precipitation index for BGR for the period 1901–2009 (after Harris *et al.*, 2013) d) El Niño3.4 index for the period 1856 to 2013 (after Kaplan *et al.*, 1998) e) CRU SOI for the period 1866 to 2006 (after Ropelewski and Jones, 1987).

4.4. Conclusion

A physical description of the study site has been provided. The methods used in this research have been detailed above. A description of the field techniques and laboratory procedures used to undertake this research, i.e. collection and preparation of stem discs, age determination methods, cross–dating techniques and correlation analyses with climate data, have been provided.

CHAPTER FIVE: RESULTS

5.1. Introduction

This chapter presents and describes the results of growth ring identification, age determination, cross–dating and correlation analyses of the responses of growth rings to climate.

5.2. Dendrochronological potential

5.2.1. Growth ring characteristics and anomalies

A. nilotica displayed distinct growth rings, delineated by a thin marginal band of terminal parenchyma (Plate 5.1). However, growth ring anomalies were present in all samples, which consisted of missing, false and discontinuous rings. Tree wounding, attributed to insect activity, occurred on samples (Plate 5.1.d). Locally absent rings were included in the construction of tree ring series while false rings were excluded. Locally absent rings were detected during cross–dating of samples. Rings that were present in the majority of samples but were absent in others were included and noted as ‘locally absent’ rings following Stokes and Smiley (1968). The tracing of each growth ring around the circumference of each sample prevented the inclusion of false rings in the rings counts and chronology development (Stokes and Smiley, 1968). Growth ring anomalies were common in older trees with increased diameter compared with younger trees with smaller diameters.

5.2.2. Age determination

5.2.2.1. GIS age determination

Due to the poor quality of the aerial photographs, individual trees were not visible on the aerial photographs from 1937, 1960, 1969, 1990 and 2001. Georeferencing was therefore only possible for satellite imagery from 2009 (Appendix B). Following the process of georeferencing, the locations of all sampled trees are displayed for the year 2009 only. The use of aerial photographs as an independent age determination method for the *A. nilotica* samples was therefore not possible before 2009.

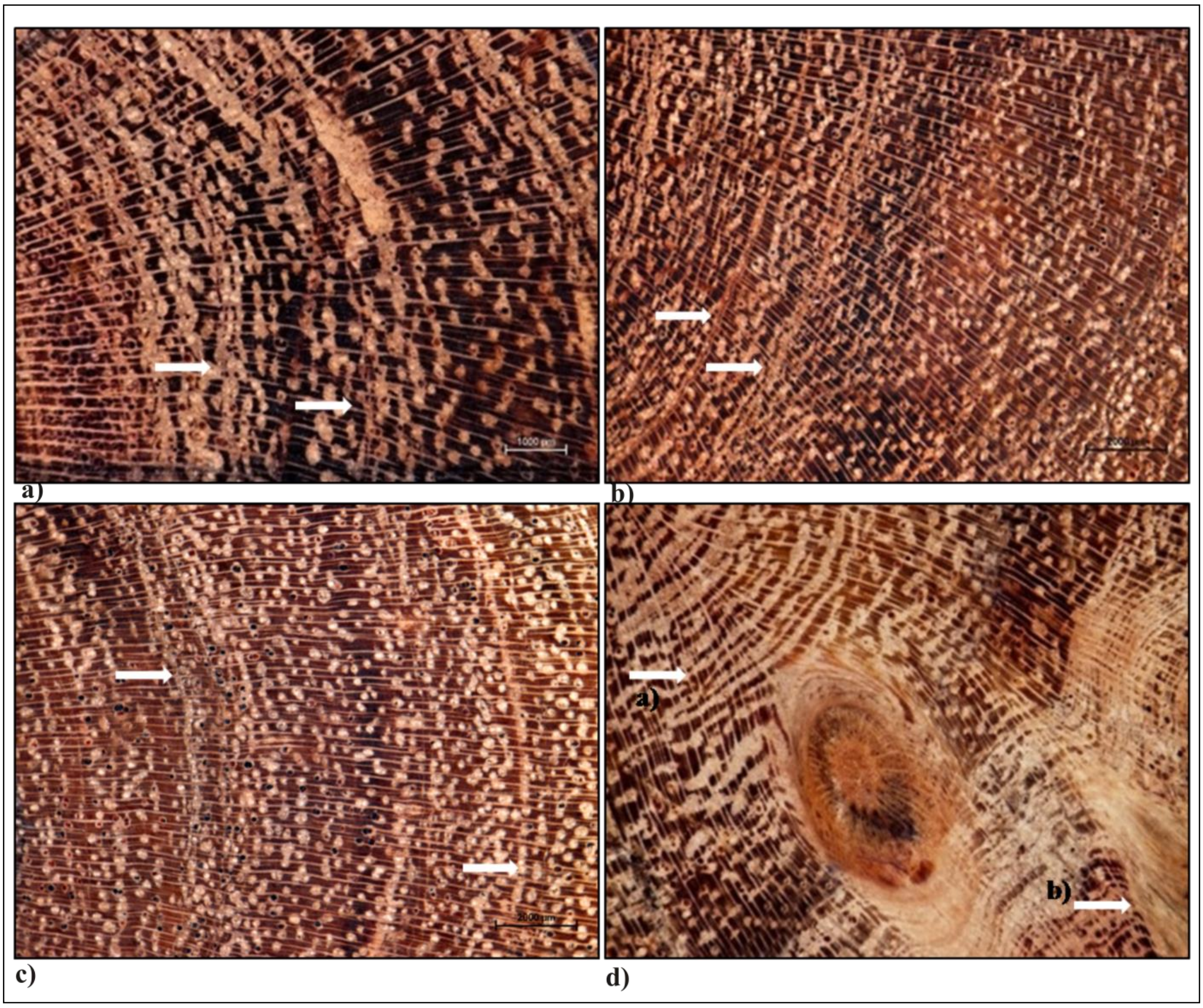

Plate 5.1: Growth rings of *A. nilotica*. a) – c) Arrows indicates position of growth rings and direction of growth. d) Arrows indicate growth ring anomalies at position a). d) Arrows indicate wounding at position b).

5.2.2.2. Ring counts

The ages of trees sampled ranged from 30 (sample 11) to 99 years (sample 3) (Figure 5.1). The average age of the samples was 58 years. The mean annual diameter increment (mad) of each tree varied between 7.98 to 16.35 mm/year with an average growth rate of 10.65 mm/year (Figure 5.1). A significant positive correlation of r=0.811* was found with tree age and stem diameter of *A. nilotica* (p<0.01*).

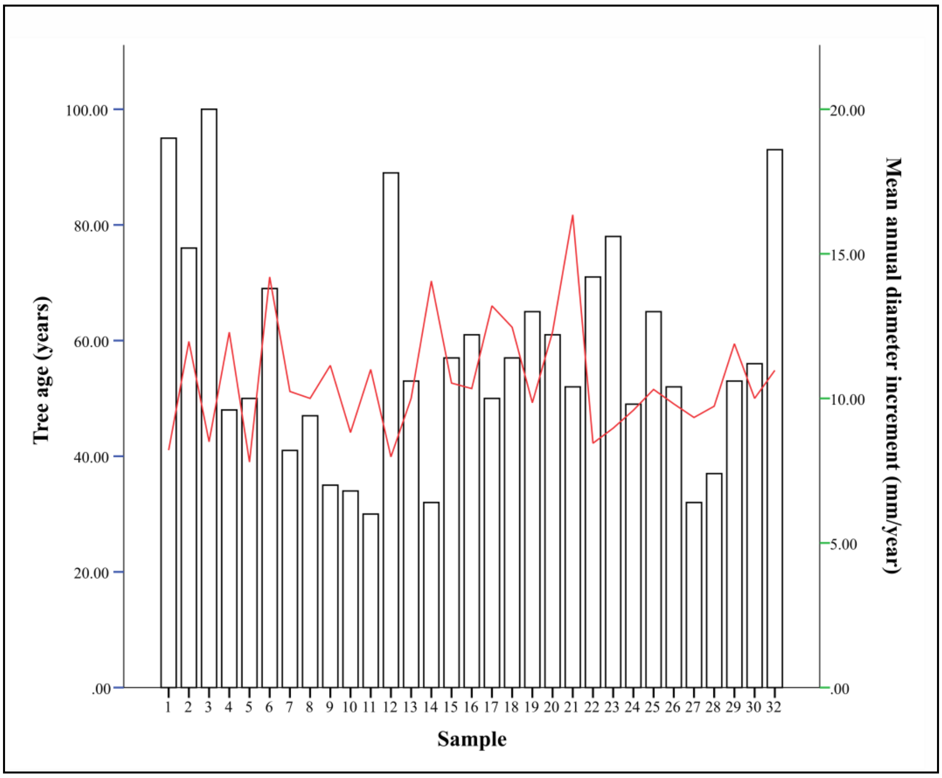

Figure 5.1: Age and mean annual diameter increment of each *A. nilotica* sample at BGR

5.2.3. Cross–dating

Cross–dating within trees was attempted for all 31 trees and average growth curves per tree were produced (Table 5.1; 5.2, Figure 5.2).

The average growth curve for each tree shows marked increases and decreases in growth throughout each growing period.

Average growth curves were used to perform cross–dating between trees. No coherent growth patterns were detected visually (Figure 5.2). The GLK values from cross–dating between trees varied from 60% to 79%, with an average of 64.5%.

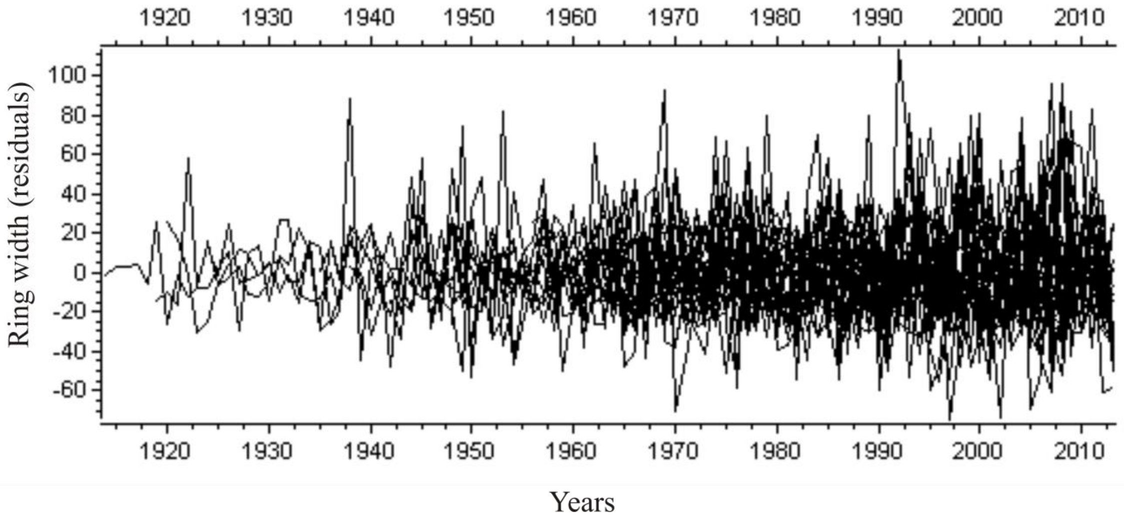

Figure 5.2: Spaghetti plot of average growth curves of 31 *A. nilotica* samples at BGR

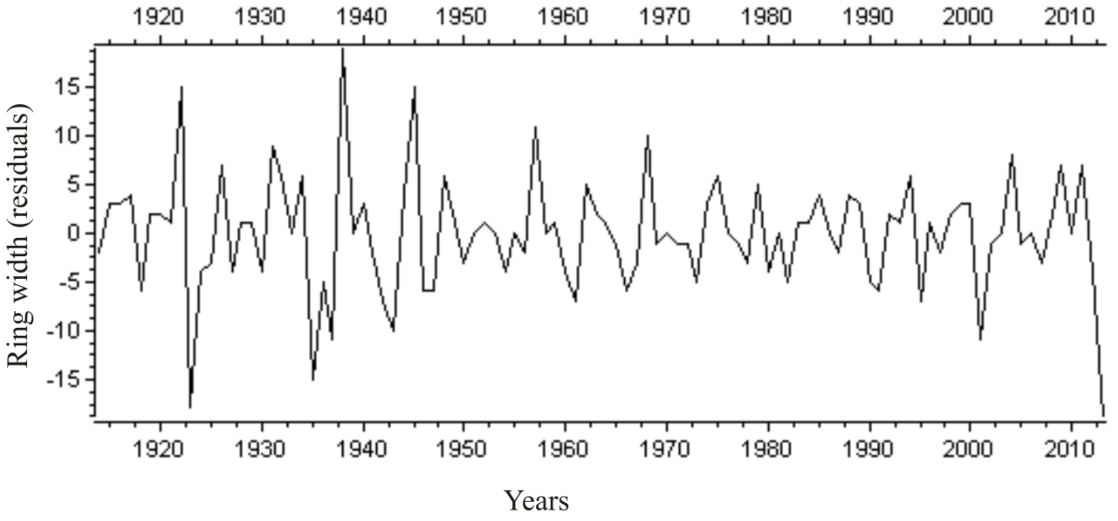

Figure 5.3: Master chronology (residuals) of *A. nilotica* at BGR

The cross–dating results were used to develop a master chronology of 99 years, ranging from 1914–2013 (Figure 5.3). Patterns of increasing and decreasing ring width are evident throughout the master chronology, with a high degree of variation. There was an overall increase in ring width between 1914–1917 followed by a decrease in growth between 1917–1918. Ring width then increased between 1918–1922. A rapid decline in ring width is apparent between 1922 and 1923. 1923–1926 showed increased ring widths. This is followed by consistent patterns of increased and decreased ring width until 1934, where ring width experienced a sharp decline between 1934–1935. Increased ring width patterns occurred between 1935–1938 followed by further decreased ring width rates until 1943. A sharp increase in ring width occurred between 1943–1945. This was followed by a sharp decrease in ring width between 1945–1946. Ring width fluctuated continuously without any rapid and sudden decreases or increases in growth between 1946–2000. A sharp decrease in ring width is noted between 2000–2001. Ring width increases until 2004, followed by an overall decrease in ring width between 2004–2007. A slight increase in ring width occurred between 2007–2009. Patterns of increasing and decreasing ring widths occurred between 2009–2011. A trend of declining ring widths is present from 2011–2013.

Low mean sensitivity of the site (–42%), indicates that the tree growth was not strongly influenced by environmental factors, and may limit further application of the master chronology produced. Autocorrelation of –0.13 suggests that tree growth was, however, more likely affected by external factors rather than internal factors (Table 5.2).

Table 5.1: GLK, t–value and CDI between average growth ring curves of 31 *A. nilotica* trees, according to sample number, from BGR (cross–dated against each other)

Sample	**Reference**	**GLK (%)**	**t–value**	**CDI**	**OVL**
1	3	65	4.6	11	37
	5	72	6.2	22	48
	6	60	5.8	17	63
	9	63	2.5	8	36
	14	73	4.1	15	33
	17	66	2.5	8	46
	19	67	4.7	13	36
	22	66	3.5	12	72
	25	65	2.9	9	58
	32	63	5.8	15	57
2	7	69	2.4	8	32
	9	61	2.7	8	36
	12	61	2.5	7	60
	13	63	2.5	8	53
	15	66	2.4	8	58
	16	61	2.1	6	52
	17	60	2.0	6	49
	22	63	4.7	14	63
	23	70	3.8	11	38
	29	61	2.9	9	49
	32	60	3.5	9	52
3	1	65	4.6	11	37
	7	61	13.9	38	33
	8	62	4.6	12	30
	10	62	2.5	8	35
	11	63	2.8	9	31

Sample	**Reference**	**GLK (%)**	**t–value**	**CDI**	**OVL**
3	17	78	2.5	9	42
4	5	63	2.8	9	45
	8	61	3.3	9	32
	16	69	2.7	8	33
	17	68	2.3	7	37
	18	60	2.3	7	47
	27	64	4.3	14	33
	32	62	4.3	13	48
5	1	72	6.2	22	48
	4	63	2.8	9	45
	14	64	4.5	15	33
	25	64	4.6	15	51
6	1	60	5.8	17	63
	9	60	2.2	7	36
	14	61	4.8	15	33
	16	66	3.5	11	61
	20	67	3.8	12	52
7	2	69	2.4	8	32
	3	61	13.9	38	33
	9	60	3.5	10	31
	10	62	2.8	9	35
	11	62	2.2	7	31
	14	63	3.2	10	32
	17	67	6.5	21	36
	29	61	4.2	13	42
	30	70	6.9	22	33
8	3	62	4.6	12	30
	4	61	3.3	9	32
	12	62	2.5	7	30
	32	60	4.3	13	46
9	1	63	2.5	8	36
	2	61	2.7	8	36
	6	60	2.2	7	36
	7	60	3.5	10	31
	13	69	2.3	8	36
	14	60	2.8	8	30
	18	66	2.4	8	36
	20	67	2.7	9	34
	24	66	2.9	9	33
	25	66	2.3	8	36
	26	66	3.3	11	36
	28	64	2.5	8	34
10	3	62	2.5	8	35
	7	62	2.8	9	35
	18	62	2.5	8	35

Sample	**Reference**	**GLK (%)**	**t–value**	**CDI**	**OVL**
10	19	66	2.8	9	35
	25	79	2.4	9	35
	32	63	2.9	9	35
11	3	63	2.8	9	31
	7	62	2.2	7	31
	18	68	2.0	7	31
	19	63	3.6	11	31
	32	65	2.6	9	31
12	2	61	2.5	7	60
	8	62	2.5	7	30
	14	64	3.5	11	33
	17	61	2.2	7	51
	18	61	4.8	12	33
	21	68	3.6	12	49
	22	68	3.3	11	72
	30	63	3.2	10	57
13	2	63	2.5	8	53
	9	69	2.3	8	36
14	1	73	4.1	15	33
	5	64	4.5	15	33
	6	61	4.8	15	33
	7	63	3.2	10	32
	9	60	2.8	8	30
	12	64	3.5	11	33
	17	63	2.6	8	33
	19	63	4.1	13	33
	20	61	3.4	10	33
	22	63	2.3	7	33
	25	67	5.8	20	33
	29	61	3.5	11	33
15	2	66	2.4	8	58
	18	69	3.9	11	33
	22	61	4.7	13	50
16	2	61	2.1	6	52
	4	69	2.7	8	33
	6	66	3.5	11	61
	26	67	3.2	10	48
17	1	66	2.5	8	46
	2	60	2.0	6	49
	3	78	2.5	9	42
	4	68	2.3	7	37
	7	67	6.5	21	36
	12	61	2.2	7	51
	14	63	2.6	8	33
	18	73	5.5	20	51
	19	70	2.3	7	41

Sample	Reference	GLK (%)	t–value	CDI	OVL
17	20	60	4.7	12	35
	21	70	2.3	7	36
	27	61	2.0	6	33
18	4	60	2.3	7	47
	9	66	2.4	8	36
	10	62	2.5	8	35
	11	68	2.0	7	31
	12	61	4.8	12	33
	15	69	3.9	11	33
	17	73	5.5	20	51
	20	74	5.3	18	43
19	1	67	4.7	13	36
	10	66	2.8	9	35
	11	63	3.6	11	31
	14	63	4.1	13	33
	17	70	2.3	7	41
	22	60	5.7	16	62
	25	61	3.5	9	48
19	28	61	5.1	16	38
20	6	67	3.8	12	52
	9	67	2.7	9	34
	14	61	3.4	10	33
	17	60	4.7	12	35
	18	74	5.3	18	43
21	2	63	2.0	6	53
	12	68	3.6	12	49
	17	70	2.3	7	36
22	1	66	3.5	12	72
	2	63	4.7	14	63
	12	68	3.3	11	72
	14	63	2.3	7	33
	15	61	4.7	13	50
	19	60	5.7	16	62
	30	61	4.9	13	38
23	2	70	3.8	11	38
	24	60	5.3	16	47
	25	66	2.0	5	30
	26	68	4.2	14	53
	29	60	2.7	8	54
24	9	66	2.9	9	33
	23	60	5.4	16	47
25	1	65	2.9	9	58
	5	64	4.6	15	51
	9	66	2.3	8	36
	10	79	2.4	9	35
	14	67	5.8	20	33

Sample	Reference	GLK (%)	t–value	CDI	OVL
25	19	61	3.5	9	48
	23	66	2.0	5	30
26	9	66	3.3	11	36
	16	67	3.2	10	48
	23	68	4.2	14	53
	29	68	2.2	7	42
	32	63	3.8	12	51
27	4	64	4.3	14	33
	17	61	2.0	6	33
28	9	64	2.5	8	34
	19	61	5.1	16	38
29	2	61	2.9	9	49
	7	61	4.2	13	42
	14	61	3.5	11	33
	23	60	2.7	8	54
	26	68	2.2	7	42
30	7	70	6.9	22	33
	12	63	3.2	10	57
30	22	61	4.9	13	38
32	1	63	5.8	15	57
	2	60	3.5	9	52
	4	62	4.3	13	48
	8	60	4.3	13	46
	10	63	2.9	9	35
	11	65	2.6	9	31
	26	63	3.8	12	31

Table 5.2: Descriptive statistics of master chronology

Descriptive statistics	Master chronology
Age range of trees (years)	31—100
Age (years)	99
Autocorrelation	–0.13
Mean sensitivity (%)	–42
Number of trees (radii)	31 (100)
Standard deviation (mm)	6
Time span (years)	1914—2013
Variance (mm)	36

5.3. Dendroclimatological potential

5.3.1. Correlation analyses of response of growth rings to local climate

Correlation analysis was conducted between the master chronology and monthly data for four local environmental variables (minimum temperature, maximum temperature, combined minimum and maximum temperature, precipitation).

Significant correlations ($p \leq 0.05^*$) were found for local precipitation during the month of April ($r = -0.355$), and minimum temperature during month of July ($r = -0.367$) (Figure 5.4). Correlations between the master chronology and maximum temperature were not significant (Figure 5.4). There were no significant correlations found within the averaged sum of minimum and maximum temperature dataset.

Growth responses with locally averaged rainy season (October through March) climatic data for all six environmental variables was investigated. This revealed a positive relationship between local precipitation and growth during the rainy season. However, no significant correlations were found for any of the environmental variables tested.

5.3.2. Correlation analyses of response of growth rings to additional climate indices

Additionally, the tree ring series was investigated using regional climate indices, downscaled to the quarter degree squared scale (CRUTS3.21). Five climate variables were used, *viz.* minimum temperature, maximum temperature, precipitation, SOI and El Niño3.4.

No significant correlations ($p \leq 0.05^*$) were found with the regional precipitation index (Figure 5.5). Similarly, no significant correlations ($p \leq 0.05^*$) were found with the regional minimum and maximum temperature indices (Figure 5.5). A positive relationship was found between tree growth during the rainy season and the precipitation index. Overall, the relationship between tree growth and temperature was negative. Tree growth was negatively correlated with minimum and maximum temperature indices during the rainy season.

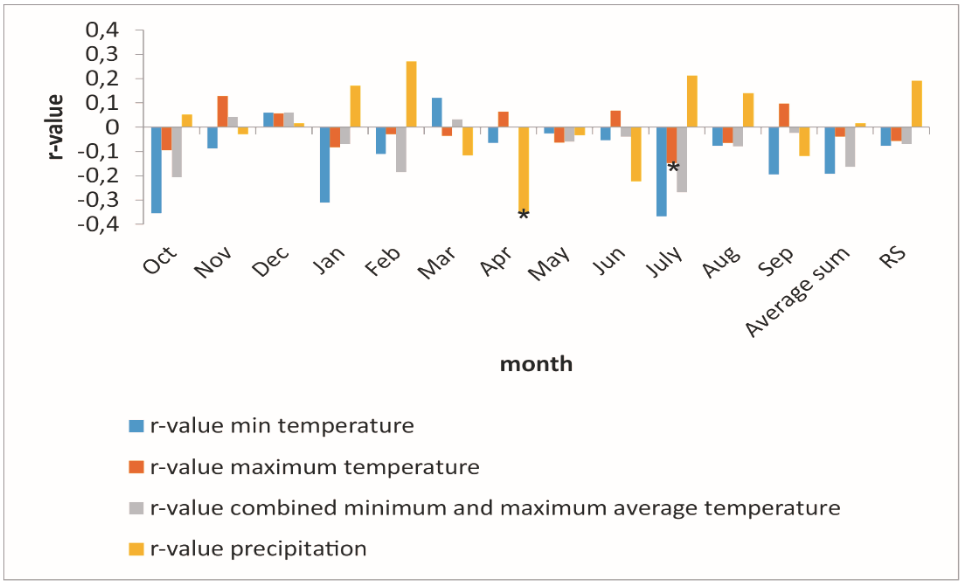

Figure 5.4: Correlations between the master chronology and local minimum and maximum temperature and precipitation data for BGR for the period 1982–2012. Climate data used are monthly (October to September), total averaged sum of each variable (Average sum) and rainy season data (RS; October-March). *Denotes significant correlations ($p \leq 0.05$*).

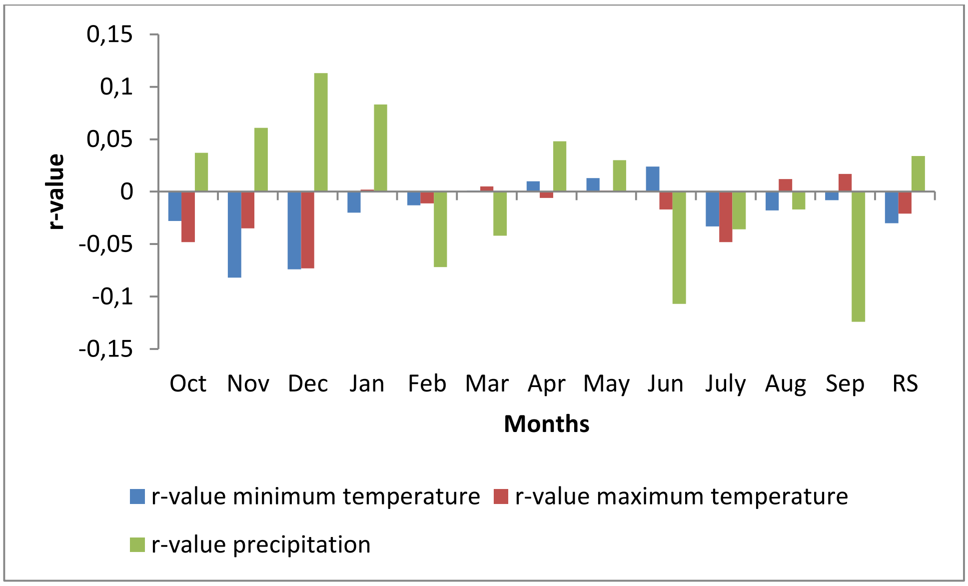

Figure 5.5: Correlations between the master chronology and CRUTS3.21 data for BGR for the period 1914–2009. Climate data used are monthly (October to September), and rainy season data (RS; October-March). *Denotes significant correlations ($p \leq 0.05$*).

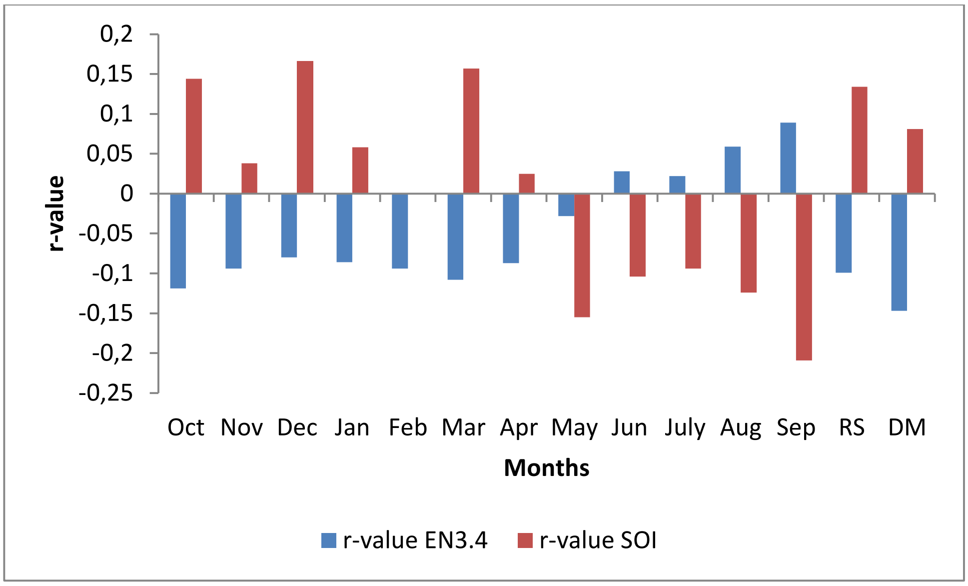

Figure 5.6: Correlations between the master chronology and CRU El Niño3.4 (EN3.4) and SOI indices for the period 1914–2013 are provided. RS covers the rainy season (October-March). DM covers the months December of the previous year to May of the current year. *Denotes significant correlations ($p \leq 0.05$*).

The correlation analysis of SOI and El Niño3.4 with the master chronology revealed no significant relationships (Figure 5.6). Nevertheless, correlations between tree growth and SOI were positive during the growing season and between the months of December to May when the ENSO signal is the strongest in southern Africa. Correlations with the El Niño3.4 index were negative during the rainy season and between December to May.

5.4. Conclusion

In conclusion, age determination was conducted for *A. nilotica*, with annual growth rings detected and measured on 31 samples with trees ranging in age from 30 to 99 years old. Cross–dating was attempted, with GLK values suggesting successful cross–dating, and a 99-yr master chronology was produced. However, the low mean sensitivity of the site indicates that the trees are not responding to environmental conditions and may call into question the reliability of the cross–dating results and master chronology produced. Correlation analysis was conducted between the master chronology and four local climate variables, and five regional climate indices. Correlation analyses revealed a lack of significant relationships between the growth of *A. nilotica* and climatic data.

CHAPTER SIX: DISCUSSION

6.1. Introduction

The master chronology developed for *A. nilotica* at Bonamanzi Game Reserve (BGR) is compared with past dendrochronological and dendroclimatological studies from subtropical and tropical Africa.

6.2. Dendrochronological potential

6.2.1. Growth ring characteristics and anomalies

The dendrochronological potential of *A. nilotica* was assessed using microscopic ring counts. The presence of annual growth rings defined by thin parenchyma bands occurred on all samples of *A. nilotica*, although growth ring anomalies such as double parenchyma were common (cf. February *et al*., 2006). As the trees were sampled in a summer rainfall region, with a predictable winter dry season, rings are likely to be annual in nature (Trouet, 2004). Due to the deciduous nature of *A. nilotica*, cambial dormancy occurs during the dry season resulting in the formation of growth ring boundaries, delineated by terminal parenchyma (Fichtler *et al*., 2004; Gebrekirstos *et al*., 2008). Terminal parenchyma bands were distinguished by their fineness and uniformity in appearance, as this is a notable feature of the Fabaceae family (Trouet *et al*., 2006). Clearly defined rings and ring anomalies on samples of the same species are common in the southern hemisphere (Worbes, 2002). Annual rings defined by parenchyma bands were distinguishable on *Acacia* species from Kenya and Ethiopia, though several studies have highlighted growth ring issues within the genus (e.g. Maingi, 2006; Gebrekirstos *et al*., 2008; 2009).

Problems of double parenchyma, and hence difficulties defining growth rings of *A. nilotica* were similarly experienced by February *et al*., (2006) and other *Acacia* species by Gebrekirstos *et al*. (2008). This was particularly the case for the youngest, outermost rings (February *et al*., 2006). The occurrence of wedging rings could be attributed to competition for resources, particularly light and water (Worbes, 2002; Gebrekirstos *et al*., 2008). Changes in light saturation due to competition, change the direction of incoming light, resulting in uneven growth around the tree's full circumference, i.e. wedging rings (Worbes, 2002; Gebrekirstos *et al*., 2008). Fire may have contributed to the occurrence of wedging rings due to environmental stresses, resulting in increased resource competition. Fires were used prior to 2004 to control the spread and distribution of *Chromolaena* in Bonamanzi Game Reserve (BGR) (Greenland, 2012). However, fire scars were present on only one *A. nilotica* sample, suggesting that fires may not have been widespread in BGR or of a high enough intensity to affect *A. nilotica*.

Discontinuous rings posed a problem on all *A. nilotica* samples. Discontinuous rings are common in summer rainfall regions as most water becomes available after growth begins (Hughes *et al*, 1982; Trouet, 2004; Jones *et al*., 2009). The occurrence of tree wounds, possibly due to insect and fungal activity, may have increased the occurrence of ring anomalies (Schmitt *et al*., 1995). Insect and fungal activity cause stresses on the plant which may lead to a decline in tree growth and ultimately death (Schmitt *et al*., 1995). Tree wounds cause the rapid death of parenchyma cells in close proximity to the tree wound. This may cause the formation of indistinct, missing and discontinuous rings (Schmitt *et al*., 1995). Discontinuous rings may be due to periods of none or slow growth that subtropical trees undergo to survive harsh environmental conditions (Norström *et al*., 2005). The presence of false rings on samples is likely due to the distinct seasonality of rainfall in KwaZulu–Natal (Trouet, 2004).

6.2.2. Age determination and cross–dating

The mean annual diameter increment (mad) of each tree (7.8mm/year to 16.35 mm/year) corresponds with findings of *Acacia* species by Gourlay (1995) and is significantly higher than findings by Gebrekirstos *et al*. (2009). A positive significant correlation between tree age and diameter for *A. nilotica* suggests that tree age may be extrapolated from stem circumference. Studies on tree age and stem circumference *A. erioloba* by Steenkamp *et al*. (2008) showed similar results as a positive relationship was found between tree ages and stem diameter. Additionally, Therrell *et al*. (2007) reported a positive relationship between tree age and diameter for *P. angolensis* from southern Africa.

A. nilotica trees ranged between 32 to 100 years old with a mean age of 58 years. This is considerably older than the trees from Hluhluwe-Imfolozi sampled by February *et al*. (2006) which ranged between 29–36 years. Comparisons between ring counts and radiocarbon dates on *A. nilotica* from Hluhluwe-Imfolozi indicates that ring counts underestimate tree age by 30 to 37% (February *et al*., 2006). Thus, ring counts lack temporal precision and should be treated as a minimum tree age.

According to Smythe *et al*., (2001), *A. nilotica* became dominant in the Hluhluwe region during the 1960's when there was increased grazing pressure and reduced fire frequencies. Twelve trees in this research were established during the 1960's and 1970's according to ring counts. This is in keeping with the theory by Smythe *et al*., (2001). February *et al*. (2006) found similar dates of establishments on *A. nilotica* and *Acacia karoo* from Hluhluwe. According to dendrochronological analysis in this research, *A. nilotica* was present in the region as early as 1914.

Cross–dating was attempted for the BGR samples. Although GLK values suggest that this produced a reliable master chronology, the low mean sensitivity of the site reduced confidence in the final result. The weak mean sensitivity (–42%) of the master chronology presented suggests that the *A. nilotica* trees used in this research were not particularly sensitive to environmental conditions, and may reflect inaccuracies in the cross–dating process. Attempts at cross–dating of *A. nilotica* by February *et al*. (2006) using the methods described by Stokes and Smiley (1968) were similarly unsuccessful. February *et al*. (2006) used COFECHA software (Holmes, 1983) to verify and correct cross–dating, however this did not improve the results suggesting that ring width drivers were not environmental (February *et al*., 2006).

6.3. Dendroclimatological potential

6.3.1. Correlation analysis of response of growth rings to climate

Correlation analysis indicated weak overall relationships between tree growth and a range of local climate variables, and regional climate indices. This is discussed in detail in the following paragraph, however, the possibility that cross–dating was unreliable cannot be discounted, especially given low mean sensitivity values.

The deciduous nature of *A. nilotica* would lead one to believe that there would be stronger correlations to climatic parameters, especially precipitation, as trees are leafless during the dry season (Smith and Goodman, 1987). The phenology of *A. nilotica* is therefore assumed to be firmly synchronized with the seasonality of precipitation. Flowering and fruiting begin to occur during the spring. This seasonality in growth suggests that radial growth is restricted to the summer rainfall season. This assumption would support the annual nature of growth rings of *A. nilotica*. Results indicated a positive correlation between tree growth and precipitation during the rainy season, suggesting that rainfall may influence tree growth, despite the non-significance of the correlation. The significant correlation with growth and precipitation during the month of April may be attributed to the end of the rainy season.

A. nilotica has a well-developed, deep rooting system allowing for water absorption from soil water reserves throughout the year (Enquist and Leffler, 2001). This allows *A. nilotica* to maintain a positive water balance during the dry season which may explain the non–significance of the correlation (Enquist and Leffler, 2001). Gourlay (1995) found strong positive correlations between annual rainfall and ring width for *Acacia* species. Furthermore, Gebrekirstos *et al*. (2008) found positive correlations between ring width and precipitation for *Acacia* species. Additionally, Hall (1976) found that precipitation patterns in the Karkloof, KwaZulu–Natal were likely to limit growth of *P. falcatus*.

The *A. nilotica* samples analysed were used to develop a master chronology spanning 99 years. This is considered a relatively long time frame as all the trees sampled in this research were used to build the chronology. However, a large proportion of trees used in this research were fairly young. Young trees do not follow strong seasonal patterns of growth to the extent of older trees (Worbes, 2002). This may be a cause for the weak correlation present between precipitation and tree growth. Additionally, the low correlations with the master chronology and precipitation may be attributed to competition for water resources. As the trees grow in a summer rainfall region, the seasonality of precipitation may lead to strong competition for water resources during the dry period, which may negatively affect the growth of *A. nilotica*. This is further supported by the overall negative correlations of tree growth to precipitation during the dry season.

The negative correlation between all local temperature datasets and growth during the rainy season suggests that temperature may not be a limiting factor on tree growth. Generally, there is an overall negative correlation present between all local temperature datasets (minimum, maximum and averaged sum) and growth, including a significant negative correlation during the month of July. Similar results were found with the CRUTS3.2 temperature dataset. These results may suggest that temperature is not a growth limiting factor for *A. nilotica*. This is in accordance with Hall (1976) who states that due to the distinct seasonality in rainfall in KwaZulu–Natal, precipitation and not temperature is more likely to be a growth limiting factor. According to Fichtler *et al.* (2004), who also found negative correlations to temperature for *B. africana* and *P. angolensis*, negative correlations to precipitation may be attributed to the exponential increase of plant respiration with increasing temperatures. This would result in a greater loss of assimilated carbon as an energy source. Conversely, Gourlay (1995a) found a significant correlation between minimum temperatures with ring width. This may indicate that different *Acacia* species have different growth limiting factors. Dunwiddie and LaMarche (1980) recorded positive responses to high temperature suggesting temperature as a growth limiting factor for *W. cedarbergensis* from Die Bos, Cape Town.

According to SAWS (2013), drought years occurred in South Africa between 1964–1970, 1991–1995 and 2002–2005. Tyson *et al.* (1997) states the occurrence of dry years in South Africa from the early to mid 1980’s and early to mid 1990’s. The master chronology showed an overall decrease in growth between 1964–1970, albeit an increase in growth occurred between 1966–1968. The master chronology shows erratic growth between the mid 1980’s to the mid 1990’s, possibly highlighting the effect of high temperatures and decreased precipitation as likely limiting factors to tree growth. This could be attributed to a scarce water supply and competition among trees for water resources. An increase in tree growth occurred between 2002–2004 followed by a sharp decrease in growth between 2004–2005. Local climate data showed an increase in precipitation between 2002–2004 followed by a decrease in precipitation the following year. This explains the trend in the master chronology between these years (2002–2005), further corroborating the effect of precipitation on tree growth. However, Worbes (2002) indicates that temperature is a growth limiting factor for trees in the southern hemisphere. Temperatures in northern KwaZulu–Natal are high with a humid climate, which leads to increased evaporation rates (Verheyden *et al.*, 2005). Therefore, despite distinct rainfall seasonality, it is possible that a combination of temperature and precipitation may be more likely to limit tree growth. This may further explain the erratic growth patterns during the mid 1980’s to the mid 1990’s, possibly indicating that *A. nilotica*, is affected by both temperature and precipitation patterns.

The positive non–significant correlation with Southern Oscillation Index (SOI) and the master chronology during the rainy season and overall negative correlations present within the SOI index and growth during the dry season suggest that the growth rate of *A. nilotica* is affected by the El Niño Southern Oscillation (ENSO) phenomena. ENSO can therefore be considered to be a growth limiting factor for *A. nilotica*. South Africa generally experiences dry conditions and receives below average rainfall during El Niño conditions, it is therefore assumed by the negative correlation present with the El Niño3.4 index and tree growth during the rainy season (October through March) and the early months of the dry season (April and May) that *A. nilotica* responds by a decrease in growth during El Niño conditions and an increase in growth during La Niña conditions. Precipitation is once again likely to be a growth limiting factor for *A. nilotica*. An increase in growth during La Niña conditions, when South Africa generally experiences higher than average rainfall and moist conditions is likely to occur.

However, correlation analysis with El Niño3.4 index showed overall positive correlations for the mid to end of the dry season. As El Niño usually brings about dry conditions in South Africa, regional temperature may be considered to be a growth limiting factor of *A. nilotica* during dry conditions. According to Enquist and Leffler (2001), some tree species, such as *A. nilotica*, may show differing responses to local and regional climatic variables. Gebrekirstos *et al*. (2009), found a strong correlation between *Acacia* species in Ethiopia and precipitation values during El Niño years. Fichtler *et al*. (2004) noted a positive correlation between El Niño years and tree growth for *P. angolensis* and *B. africana* from Namibia. Positive correlations were found between SOI and *Isoberlinia* and *Brachystegia* in western Tanzania (Trouet *et al*., 2001).

The ENSO effect in southern Africa is the strongest between December to May, i.e. mid to end of the rainy season (Fichtler *et al*., 2004; Trouet *et al*., 2010). The El Niño3.4 index displayed a non–significant negative correlation for this time period, suggesting a decrease in growth during El Niño3 years. A positive correlation occurred during the same period with the SOI index and tree growth. These results further indicate the effect of precipitation on tree growth. Results from a study by Trouet *et al*. (2006; 2010) indicated a negative response of tree growth of *B. spiciformis* to ENSO. *B. africana* and *P. angolensis* from Namibia showed strong positive responses of tree growth to ENSO (Fichtler *et al*., 2004). Strong positive correlations with *P. angolensis* from Zimbabwe and ENSO were indicated by Therrell *et al*. (2006). *B. africana* and *P. angolensis* displayed conflicting results to the El Niño3.4 index and the SOI effects, as is the case with *A. nilotica* (Fichtler *et al*., 2004). The variable time lag between the occurrence of ENSO phenomena in the Pacific Ocean and its effect on southern Africa could have caused the lack of significant correlations present between the ENSO indices and tree growth (Trouet *et al*., 2001; Valimba et al., 2006). As the results from correlation analyses with the master chronology and El Niño3.4 index and SOI are somewhat contradictory, long term studies are required to better understand the spatiotemporal variability of the ENSO phenomenon (Trouet *et al*., 2010). Tree ring series are particularly useful in these studies due to their annual resolution (Trouet *et al*., 2010).

This study attempts cross–dating of *A. nilotica* on 31 samples from BGR in northern KwaZulu–Natal, South Africa. *A. nilotica* has displayed some potential as a dendrochronological species due to the presence of annual growth rings, resulting in the development of a 99 year regional chronology. The weak mean sensitivity of the master chronology must be acknowledged as a potential limitation of the correlation analysis that followed. Additional studies on *A. nilotica* tree ring chronologies are recommended to better constrain ring width variation between individual trees before palaeoclimate reconstruction can be attempted.

CHAPTER SEVEN: CONCLUSION

7.1. Main conclusions

Dendrochronology and dendroclimatology in the southern hemisphere is hampered by a lack of suitable tree species which exhibit clear annual growth rings. However, high resolution palaeoclimatic archives, such as tree ring series, are vital to improving our understanding of past climate change. This research has explored the potential of *A. nilotica* in KwaZulu-Natal for use in dendrochronology. Despite the occurrence of growth ring anomalies on all samples, annual growth rings, were detected, defined by fine terminal parenchyma bands.

Cross–dating was attempted for the 31 disc samples, yielding a 99-yr master chronology supported by high GLK values. However, the low mean sensitivity of the master chronology reduce confidence in the cross–dating results. Moreover, correlations of the master chronology with local climate variables and regional climate indices were weak overall, indicating poor dendroclimatological potential of *A. nilotica*.

7.2. Review of aims and objectives

The aim of this research was to assess the potential of *Acacia nilotica* (L.) for dendrochronological and dendroclimatological research with a view to develop a palaeoclimate reconstruction for the Zululand region. This was attempted through a number of research objectives that are reviewed below.

i. **To extract ring samples from *A. nilotica* trees and to process discs such that growth rings can be easily identified and counted**;

After consultation with appropriate literature, 31 full stem discs of a range of sizes were sampled from a single area of the Bonamanzi Game Reserve (BGR). Discs were polished to a high shine for stereomicroscopic analysis.

ii. **To acquire temporal information of the samples through microscopic tree ring counts resulting in age determination of each tree;**

LINTAB equipment and TSAP software were used to determine the age of each tree through microscopic ring identification and counts along multiple radii for comparative purposes. Careful attention was paid to note the presence of missing and false rings, and other growth anomalies, thereby improving the accuracy of the ring counts.

iii. **To assess the dendrochronological potential of *A. nilotica* through cross–dating procedures and following successful cross–dating, develop a master chronology for *A. nilotica*;**

Visual analysis and TSAP software were used in conjunction to cross–date all 31 samples. A master chronology for BGR was developed, spanning a length of 99 years from 1914 to 2013. High GLK values suggested that cross–dating was successful, however, a lack of coherent growth patterns between individuals and low mean sensitivity are acknowledged as limitations of the cross–dating results. Previous cross–dating attempts by February *et al.*, (2006) reported similar difficulties with cross–dating this species.

iv. **To attempt to correlate the master chronology with instrumental climatic data to assess the dendroclimatological potential of *A. nilotica*;**

Correlation analysis of ring widths with locally averaged instrumental climate data, i.e. minimum temperature, maximum temperature and precipitation, from weather stations situated around BGR, was performed at a monthly, annual and seasonal (rainy season) scale for the common period 1982–2012. In addition, ring widths were correlated with observational data from the CRU TS3.21 climate index for available years (1914–2009), CRU SOI dataset and the El Niño 3.4 index for the years 1914–2013. Non–significant correlations were found between the tree growth response and local and regional climate, except for April with the local precipitation dataset and July with the local minimum temperature dataset.

v. **To produce a palaeoclimatic reconstruction for the region following successful climatic correlations**

> The low sensitivity values of the master chronology, coupled with a weak overall relationship between tree growth and climate, precluded palaeoclimate reconstruction from the tree ring series presented.

7.3. Future research considerations and conclusions

Careful site and species selection are essential to the success of dendrochronological and dendroclimatological research (Lilly, 1977; Trouet, 2004). Sampling strategies in southern Africa should focus on the collection of full stem discs as opposed to increment cores to avoid problems of ring anomalies (Stahle *et al*., 1999a; Trouet, 2004; 2006). However, due to permissibility required to obtain full stem discs, increment cores are sometimes the only viable option and should therefore be collected and analysed with caution.

This research has demonstrated some potential to develop an annual chronology using *A. nilotica* tree ring series for northern KwaZulu–Natal. The development of high resolution chronologies, are crucial to understanding climate variability of the recent past. A network of tree ring chronologies would extend the spatial and temporal scale of high resolution palaeoclimatic records, further increasing our understanding of contemporary climate variability. Additionally, other longer lived tree species may be analysed for their dendrochronological potential and if possible, radiocarbon analyses on these species can temporally expand the record. Geochemistry may be possible on other tree species from the region, further strengthening the chronology and possibly allowing for climate reconstruction.

Dendrochronology and dendroclimatology have been successfully studied in the northern hemisphere but remains widely under developed in lower latitudes. The attempt at cross–dating of *A. nilotica* adds to the body of palaeoecological work available for southern Africa, particularly South Africa and can additionally contribute to the existing global network of tree ring studies. This network primarily covers the northern hemisphere and therefore tree ring series from the southern hemisphere, particularly ones at low latitude as South Africa are likely to be valuable (Trouet, 2004).

This research opens up the possibility of further investigating dendrochronology in KwaZulu–Natal. Future research directions should focus on assessing the dendroclimatological potential of other *Acacia* species. Site comparisons between the same species are likely to provide a better developed regional chronology, providing a clearer assessment of climate sensitivity. This would allow for isotopic approaches to be applied, possibly providing stronger climate signals, with a high level of precision. Disturbance events such as fire frequencies and insect outbreaks may be investigated. These further investigations may lead to an increased understanding of local and regional climate change. Combined with other proxy records, a more complete synthesis of late Holocene climatic and environmental change in KwaZulu–Natal is possible. Dendroecological studies, i.e. the investigation of net primary productivity and determination of carbon sinks and sources and sources are crucial to understanding climate change and can inform conservation priorities (Jones *et al*., 2009). Biomass production and tree growth rates can be used to assess resource potential of forests, resulting in better forest management (Stahle *et al*., 1999b). Such studies should therefore be prioritized (Stahle *et al*., 1999b).

Attempts at cross–dating and the subsequent development of a 99 year regional chronology may support the dendrochronological potential of *A. nilotica*. The dendroclimatological potential of *A. nilotica* should be further investigated, possibly through isotopic analysis so that specific climatic conditions could be inferred. This study has contributed to tree ring research in southern Africa adding to the body of palaeoecological information available for southern Africa.

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APPENDIX A

Field data and length of each tree ring series and time span covered

Tree number	Latitude	Longitude	Elevation (m)	Tree height (m)	Tree dbh (mm)	Length (years)	Date begin (years)	Date end (years)
1	–28.01167	32.29428	50	4	780	96	1918	2013
2	–28.01111	32.29436	55	4.5	910	77	1937	2013
3	–28.0107	32.29415	51	3.5	850	101	1913	2013
4	–28.01121	32.29348	55	4.5	590	49	1965	2013
5	–28.01151	32.29276	49	2	390	51	1963	2013
6	–28.01137	32.29239	55	5.5	980	70	1944	2013
7	–28.01127	32.29203	54	3	420	42	1972	2013
8	–28.01126	32.29198	46	4	470	48	1966	2013
9	–28.01113	32.29195	53	3.5	390	36	1978	2013
10	–28.01201	32.2937	56	2.5	300	35	1979	2013
11	–28.01369	32.2911	54	2.5	330	31	1983	2013
12	–28.01394	32.29098	55	4	710	90	1924	2013
13	–28.01388	32.291	54	3	530	54	1960	2013
14	–28.01393	32.29097	56	3.5	450	33	1981	2013
15	–28.01402	32.29072	56	3.5	600	58	1956	2013
16	–28.01416	32.29074	54	3	630	62	1952	2013
17	–28.01424	32.2908	52	3	660	51	1963	2013
18	–28.01458	32.29087	55	3	710	58	1956	2013
19	–28.01458	32.29094	58	2.5	640	66	1948	2013
20	–28.01453	32.29086	55	2.5	750	62	1952	2013
21	–28.01542	32.29082	54	3	850	53	1961	2013
22	–28.01561	32.29077	54	3.5	600	72	1942	2013
23	–28.01568	32.2906	54	2.5	700	79	1935	2013
24	–28.01578	32.29079	55	2.5	470	50	1964	2013
25	–28.01578	32.29103	55	3	670	66	1948	2013
26	–28.01566	32.29044	48	2.5	510	53	1961	2013
27	–28.0155	32.29057	49	3	300	33	1981	2013
28	–28.01537	32.29053	50	2	360	38	1976	2013
29	–28.01542	32.29042	50	2.5	630	54	1960	2013
30	–28.01548	32.29031	49	2.5	560	57	1957	2013
31	–28.01619	32.28973	54	4.5	1020	94	1920	2013
32	–28.01692	32.29036	55	3.5	930	–	–	–

APPENDIX B

Residual ring widths for indexed BGR chronology

Year	**Residual ring widths**
1914	–2
1915	3
1916	3
1917	4
1918	–6
1919	2
1920	2
1921	1
1922	15
1923	–18
1924	–4
1925	–3
1926	7
1927	–4
1928	1
1929	1
1930	–4
1931	9
1932	6
1933	0
1934	6
1935	–15
1936	–5
1937	–11
1938	19
1939	0
1940	3
1941	–2
1942	–7
1943	–10
1944	4
1945	15
1946	–6
1947	–6
1948	6
1949	1
1950	–3
1951	0
1952	1
1953	0
1954	–4
1955	0

Year	**Residual ring widths**
1956	–2
1957	11
1958	0
1959	1
1960	–4
1961	–7
1962	5
1963	2
1964	1
1965	–1
1966	–6
1967	–3
1968	10
1969	–1
1970	0
1971	–1
1972	–1
1973	–5
1974	3
1975	6
1976	0
1977	–1
1978	–3
1979	5
1980	–4
1981	0
1982	–5
1983	1
1984	1
1985	4
1986	0
1987	–2
1988	4
1989	3
1990	–5
1991	–6
1992	2
1993	1
1994	6
1995	–7
1996	1
1997	–2
1998	2
1999	3
2000	3
2001	–11

Year	**Residual ring widths**
2002	–1
2003	0
2004	8
2005	–1
2006	0
2007	–3
2008	2
2009	7
2010	0
2011	7
2012	–4
2013	–19

APPENDIX C

Location of *A. nilotica* samples at Bonamanzi Game Reserve for the year 2009 (LANDSAT imagery)

APPENDIX D

Weather station id and gps co-ordinates

Name	ID	GPS co-ordinates	
		Latitude (˚)	Longitude (˚)
Babanango	03373825	–28.33	31.20
Pongola	0410175X	–27.57	31.57
Vryheid	03725271	–27.77	30.78
Ulundi	03377382	–28.27	31.38
Charters Creek	0339732A9	–28.20	32.40
Makatini	04113232	–4.22	32.15
Mbazwana	04121486	–27.47	32.57