**REPORT TO THE WATER RESEARCH COMMISSION
ON THE PROJECT:**

AN ASSESSMENT OF THE POTENTIAL FOR USING STABLE CARBON ISOTOPE RATIOS OF WOOD CHARCOAL AS A CLIMATE INDICATOR

EC February
South African Museum
Cape Town

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**EXECUTIVE SUMMARY OF A
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Introduction

The emphasis of this project was on the evaluation of a new technique in climate reconstruction based on the stable carbon isotope ratios of charcoal excavated from archaeological sites. Incorporated within this objective was the reconstruction of the rainfall history of the last 300 years in South Africa.

The main aims of the project were:

a. To determine the stable carbon isotope ratios of contemporary wood samples across a climate gradient as well as across the diameter of a tree as a relative rainfall indicator.

b. Evaluate the stable carbon isotope ratios of charcoal from archaeological sites as a rainfall indicator.

c. Extend the rainfall record further back in time using the xylem anatomy of radiocarbon dated charcoal from archaeological sites.

d. Extend the results obtained from the xylem anatomy to the results obtained from stable carbon isotope ratios of the same assemblages.

e. Assess the dendrochronological potential of two South African woody species.

Rationale for this project

Both the future management of present water resources and forward planning for the enhancement of water supplies require a projection on the range of climates which can be expected in the future. Such projections are made on the basis of what has occurred in the past. At present regional rainfall data sets do not extend over more than 100 years (35 stations in 1880) and register relatively short oscillations of climate (Tyson 1986). Since all climate research is based on this very limited data set, the applicability of results are often questionable.

Dendrochronology in the Northern Hemisphere provides a good climate record going back in time for thousands of years (Trenard and Langdon 1982). Dendrochronological studies in southern Africa, however, tend to focus on very few species and successful dendrochronological studies on South African woody species are destructive. Trees many hundreds of years old have to be cut down (Lilly 1977). Lilly concluded that; "*indigenous tree species in South Africa are by no means as well-suited to dendrochronological studies as their European and North American counterparts*" (1977:72). In order to dispense with the need for tree ring analysis in the summer rainfall region of southern

Africa the development of a new method for determining changes in rainfall through time is vitally important.

Furthermore, in 1986 the International Council of Scientific Unions in South Africa approved the appointment of a special committee to develop South Africa's contribution to the International Geosphere Biosphere Programme (IGBP). Subsequently the IGBP core project Global Change and Terrestrial Ecosystems (GCTE) was established to improve our understanding of how terrestrial ecosystems would react to changes in atmospheric composition, climate and land use. The main aim of this GCTE programme is to develop the capability to predict the changes in climate, CO_2 and land use on terrestrial ecosystems. Much of this prediction is based on GCM's. However, without long term accurate chronologies of climate these GCM predictions are questionable. It is therefore imperative that a range of other methods, both complementary and corroborative, for establishing longer records are developed. The use of stable carbon isotope ratios of wood charcoal as a climate indicator is one such method, the potential of which needed to be investigated.

Stable carbon isotope analysis

This study explores the potential for using stable carbon isotope measures both in tree rings and archaeological charcoal as a potential record of rainfall change through time. The hypothesis is grounded in recent research which has shown that $^{13}C/^{12}C$ ratios are good indicators of the amount of water available to plants (Freyer and Belacy, 1983; Leavitt and Long, 1986). The hypothesis is that when CO_2 is absorbed by plants the heavier ^{13}C isotope is discriminated against relative to the lighter ^{12}C isotope due to diffusion during stomatal conductance and the kinetic effect of the chemical reaction as the CO_2 is absorbed by the enzyme RuBP carboxylase. With increased water stress, stomatal closure results in reduced CO_2 uptake and therefore less discrimination resulting in more positive stable carbon isotope values. Ehleringer and Cooper (1988) sampled various species along a moisture gradient in California and identified a change in $^{13}C/^{12}C$ ratios from -24‰ in the driest habitats to -26‰ in the wetter habitats. It is this relationship between stable carbon isotope ratios of wood and the amount of water available to plants that forms the basis for the present project.

To achieve the objectives, as set out in *The main aims of the project* on page 2 of this executive summary, six developmental steps were taken.

The following is a brief summary of each of these steps.

Charcoal identification and relative abundance as an indicator of vegetation change in the Drakensberg.

This section of the report describes the methods used in the analysis of 540 pieces of charcoal from two archaeological sites situated in the foothills of the Drakensberg region of Kwazulu-Natal. The identification of wood and charcoal to genus/species level is possible because the different genera have distinctive combinations of anatomical features visible under the microscope. The archaeological samples used in this section of the project were only positively identified when compared with a modern reference collection which was obtained by sampling and charring the woody species growing in the vicinity of the archaeological sites today. Changes in the relative abundances of identified taxa within the archaeological record suggest a higher percentage of *Protea* savannah in the Drakensberg foothills in the past than what is evident today. This decline in the Protea savannah is probably caused by an increase in the number of veld fires in the area surrounding the archaeological sites rather than by a decrease in rainfall as the decline is most evident over the last 300 years as farming intensity in the area increased. The suggestion is that rather than climate change, these differences are anthropogenically induced because present burning programmes are designed to improve quality of grazing by maintaining open grassland communities.

An assessment of the dendrochronological potential of two *Podocarpus* species.

In this section of the report an attempt is made, using *Podocarpus falcatus* and *Podocarpus* latifolius, to determine a methodology for dating, cross dating and chronology development, all of which are fundamental to dendrochronology and climate reconstruction from tree rings (Fritts, 1976). The results indicate that even though whole trunk cross sections were used as advocated by Curtis et al., (1978), there is still a large percentage of error when calculating the age of these trees from ring counts. Furthermore, even if this percentage error were smaller a combination of poorly defined, locally absent and converging rings makes cross dating between different trees from the same locality an impossible task. These results suggest that because of locally absent and converging rings, future dendrochronological research using *Podocarpus* from the wetter parts of South Africa is not justifiable, especially since whole trunk cross sections have to be used in the analysis and *Podocarpus* are rare and endangered. It is possible that trees obtained from a dryer environment such as the Northern Province, Mpumalanga or the west coast of South Africa may exhibit some attributes which can be used in chronology development. Any future research should focus on cross dating and chronology development from trees collected from the drier parts of South Africa as it has been shown that in the drier areas, where moisture stress is greatest, the climate signal within the ring series is enhanced (Fritts, 1967).

The relationship between ring width measures and precipitation for *Widdringtonia cedarbergensis.*

Using *Widdringtonia cedarbergensis* from the Cedarberg Mountains, near Cape Town, two more chronologies were added to the single chronology already available (Dunwiddie and La Marche 1980). The development of these well dated ring width index chronologies was hampered by a lack of an abrupt termination in late wood growth in many of the trees. Despite this limitation the results of this study show that, with a large enough sample size, it is possible to develop well dated ring width indices from *Widdringtonia cedarbergensis.* Rainfall within the Cedarberg Mountains is however extremely variable. This variability in rainfall means that very careful site selection is necessary to develop a chronology that reflects the amount of rain sufficiently to reconstruct rainfall through time. The most promising site in the present study is that at Krakadouw. Even this chronology, however, is not sufficiently well correlated with rainfall to be used in meaningful reconstruction of annual rainfall records through time. This is the only chronology from that area of the Cedarberg. Further research should concentrate on developing further chronologies from the same area but with careful selection of specific trees which are more likely to reflect rainfall in ring width.

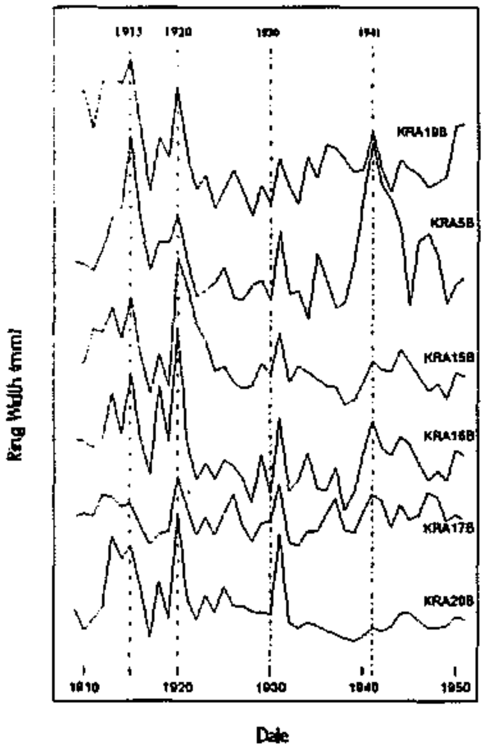

Figure 1. Portions of ring width plots for six trees from the Krakadouw site illustrating cross-dating in the period 1910 - 1950.

A $\delta^{13}C$ chronology from tree rings of *Widdringtonia cedarbergensis* during the 20th Century, climatic and environmental implications.

The previous section of this project has indicated that unlike the various *Podocarpus* species dendrochronological age determination and cross dating is possible for

Widdringtonia cedarbergensis. Correlations of ring width indices with rainfall are, however, not sufficiently high to reconstruct annual rainfall through time. Recent climate and environment reconstructions have been based on stable carbon isotope ratios in tree rings (Peng *et al.*, 1983; Freyer and Belacy, 1983; Stuiver *et al.*, 1984; Leavitt and Long, 1988, 1989), C4 plants (Marino and McElroy, 1991) and direct measures of air trapped in ice cores (Friedli *et al.*, 1986). The principal goal of this section of the report is to investigate the potential for using stable carbon isotope ratios ($^{13}C/^{12}C$) of wood cellulose from tree rings as an alternative method to ring width index analysis in climate reconstruction. Such reconstructions are based on the assumption that the ratio between the stable isotopes ^{13}C and ^{12}C can be a good estimate of water available to plants (Freyer and Belacy, 1983; Farquhar and Richards, 1984; Hubick, 1984).

The main influence on stable carbon isotope values of cellulose in C3 plants is the diffusion of CO_2 through the stomates. As atmospheric CO_2 is taken up by the plant during photosynthesis, fractionation of the carbon isotope occurs due to the width of the stomatal pore and the heat generated during the chemical reaction as the CO_2 is absorbed by the enzyme RuBP carboxylase. The proportion of ^{12}C to ^{13}C can change because ^{12}C is slightly smaller and lighter than ^{13}C and thus reacts faster. Therefore, stomatal closure during periods of moisture deficiency should lead to elevated $^{13}C/^{12}C$ ratios, as a reduction of available CO_2 during this period leads to diminished photosynthetic discrimination against the heavier ^{13}C isotope in favour of the lighter ^{12}C isotope (Francey and Farquhar, 1982). Ehleringer and Cooper (1988) sampled various species along a moisture gradient in California and identified a change in $^{13}C/^{12}C$ ratios from -24.2‰ in the driest habitats to -26.5‰ in wetter conditions. It is this relationship between carbon isotope values of wood cellulose and the amount of water available to the tree that is the main focus of this section of the report.

A 77 year stable carbon isotope chronology was developed using six trees from a site in the Cedarberg Mountains near Cape Town. The isotopic composition of wood cellulose from the growth rings of trees may document a record of $\delta^{13}C$ variations in atmospheric CO_2, represent physiological responses to environmental changes or a combination of both. The $\delta^{13}C$ record from the pooled trees at the Die Bos site does not correlate significantly with the rainfall record from Wupperthal. This correlation is not significant even when the *Widdringtonia* stable carbon isotope record is detrended for the anthropogenic CO_2 contribution. The *Widdringtonia* record does, however, indicate a strong correlation between stable carbon isotope ratios of tree rings and atmospheric carbon dioxide levels. This correlation is manifested by less negative $\delta^{13}C$ values from 1900 to 1947 and a clear decrease to 1977 which is very similar to that derived from ice core data (Friedli *et al.*, 1986) tree ring $\delta^{13}C$ chronologies from the northern hemisphere (Freyer and Belacy, 1983) and recent southern hemisphere records (Leavitt and Lara, 1994; Fig. 7). This is only the second chronology, and the first with annual resolution, to show a decline in $\delta^{13}C$ for the Southern Hemisphere. However, these results can only be substantiated by further stable carbon isotope work on tree rings not only from *Widdringtonia* but from other species in different parts of South Africa.

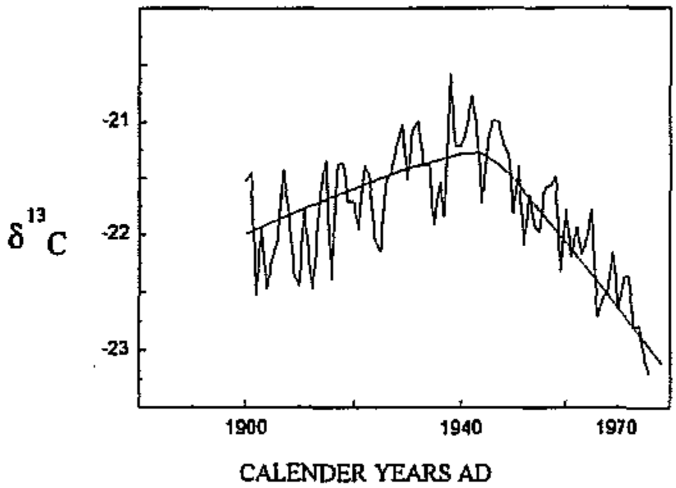

Figure 2. $\delta^{13}C$ values of *Widdringtonia cedarbergensis* from 1900 to 1977 showing the trend toward more negative values.

Relationship between water consumption plant growth and stable carbon isotope ratios in *Eucalyptus grandis* and the hybrid *Eucalyptus grandis x nitens*.

The primary objective of this study was to determine the relationship between stable carbon isotope ratios of wood cellulose and the amount of water available to the tree. To this end, cuttings of *Eucalyptus grandis* and *Eucalyptus grandis x nitens* were planted in 220 litre drums from which rainfall was excluded. One half of the individuals received a low watering treatment and the rest received a higher watering treatment. Soil moisture depletion through root uptake was monitored weekly and the removed water replaced to maintain 60 and 80 litres in the pots of the low and high watering treatments respectively. $^{12}C/^{13}C$ ratios of wood cellulose were compared for the two treatments. For *Eucalyptus grandis* and *Eucalyptus grandis x nitens*, $^{12}C/^{13}C$ ratios become less negative while plant biomass decreases as water consumption decreases. The results of the experiments suggest that $^{12}C/^{13}C$ ratios may be a useful indicator of water consumed by the tree. In both species, water availability also had a significant influence on stem diameter ($P < 0.0001$) and transverse sectional stem area ($P < 0.0001$) which increased with increased water consumption. These results suggest that the $\delta^{13}C$ values of tree wood cellulose may be useful in rainfall reconstructions, provided that the trees chosen for analysis are sensitive to changes in rainfall and that atmospheric isotope correlations are understood

	Variable	*Watering treatment*				
		Dry	*Std Dev*	*Wet*	*Std Dev*	*t test*
grandis						
	N° of plants	11		14		
	Plant mass (g)	1107	233	2055	415	****
	Stem diameter (mm)	21	1	26	2	****
	Stem area (cm^2)	3.4	0.35	5.3	0.72	****
	Water uptake (l)	349	75	723	130	****
	Height (m)	1.72	0.10	2.08	0.21	****
	N° of plants	9		14		
	δ13C, ‰	-22.5	0.45	-24.5	1.03	****
grandis x nitens						
	N° of plants	8		9		
	Plant mass (g)	944	203	1900	267	****
	Stem diameter (mm)	19	2	27	3	****
	Stem area (cm^2)	2.9	0.6	5.5	1	****
	Water uptake (l)	252	41	631	113	****
	Height (m)	1.75	0.18	2.19	0.13	****
	N° of plants	7		9		
	δ13C, ‰	-22.5	0.65	-23.5	0.72	**

Table 1. The differences between plant growth and δ13C values of *Eucalyptus grandis* and *E. grandis x nitens* after cultivation under different watering treatments. Values are means for the number of plants indicated. NS denotes no significant difference between means and *, **, ***, **** indicate significant difference between means at P< 0.05, 0.01, 0.001 and 0.0001 respectively.

A secondary objective of the study was to determine the relationship between $^{12}C/^{13}C$ ratios of *Eucalyptus* species and the integrated measure of dry matter produced per unit water use (Water Use Efficiency or WUE). In this respect, the results indicate that $^{13}C/^{12}C$ ratios of *Eucalyptus* species are not a useful indicator of WUE. Rather, less negative $\delta^{13}C$ values mean low biomass and low water consumption, but not necessarily high WUE.

Stable carbon isotope ratios in charcoal and wood cellulose of *Combretum apiculatum* and *Protea roupelliae* and relationships with rainfall.

The principal goal of this section of the report is to demonstrate the potential for using stable carbon isotope ratios of charcoal from archaeological sites as a climate indicator. To this end, samples of *Combretum apiculatum* and *Protea roupelliae* were collected along a climate gradient in the summer rainfall region of South Africa. Subsamples were charcoaled at 400°C. The results indicate that $\delta^{13}C$ values of *P. roupelliae* cellulose and charcoal are not significantly related to rainfall. *Combretum apiculatum*, however, does exhibit significant correlations between rainfall and $\delta^{13}C$ values of whole wood and cellulose. These differences in correlations between *Protea* and *Combretum* can probably be attributed to the range of particular environments to which these plants have become adapted. The $\delta^{13}C$ values of a charcoaled sample of *Combretum apiculatum* are however, not significantly related to rainfall. The reasons for this are probably related to a differential fractionation of the carbon isotopes when the cellulose is degraded during charcoalification. These results suggest that the primary objective of this study, rainfall reconstructions based on $\delta^{13}C$ values of wood charcoal from archaeological sites, is not viable. Following on this conclusion objectives c, d and e as set out on page 2 of this executive summary could not be met because there was no basis for continuing to pursue such research.

Concluding remarks.

While the final conclusion is a negative one, there are a number of positive results which have emanated from this study. The charcoal identification and relative abundance described in Chapter Two is a simple method for determining environmental change which does give information for palaeoclimatic interpretation that is independent of and will clarify data obtained by other independent methods such as xylem analysis (February, 1992).

The assessment of the dendrochronological potential of two *Podocarpus* species in Chapter Four should finally lay to rest the use of this species in dendrochronological research in South Africa. The establishment of two further chronologies to add to the one already established by Dunwiddie and La Marche (1980) makes a real contribution to the development of dendrochronology in South Africa. The potential of *Widdringtonia* is extremely important for any further research attempts to develop a high resolution rainfall record for South Africa. More dendrochronological research using this species is a definite priority not only for developing a ring width index chronology related to rainfall but also for an assessment of the anthropogenic impact on atmospheric CO_2.

The results of the stable carbon isotope analysis of *Eucalyptus* species suggests a strong relationship between $\delta^{13}C$ values and water use. These findings are not only useful for verifying the relationship between isotope values and water use but may be useful in cloning programmes where the main purpose is to identify drought tolerant and productive species that will ensure forest production in low rainfall areas.

The loss of the correlation between $\delta^{13}C$ values of *Combretum* and rainfall upon charring of the wood is also important for similar research projects working with $\delta^{13}C$ values and either archaeological or soil samples in that all charcoal would have to be removed from such samples prior to analysis because of the unknown fractionation factor.

Archiving of data

All the data as well as the slide, wood, charcoal and cellulose collections generated by this project will be appropriately stored for future retrieval at the South African Museum in Cape Town.

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PREFACE AND ACKNOWLEDGEMENTS

This study arose out of the need to develop a technique to determine changes in rainfall patterns through time in South Africa. The very limited time range of our present regional data set means that the long term variability of water supplies in South Africa is poorly understood. South Africa urgently requires high resolution (annual basis) regional data sets going back for 300 to 400 years in order to develop hypothesis on future water availability.

The research in this report emanated from a project funded by the Water research Commission. The Steering Committee responsible for the project consisted of the following persons;

Dr G.C. Green	Water Research Commission (Chairman).
Mr F.P. Marais	Water Research Commission (Secretary).
Mr H. Maaren	Water Research Commission.
Mr E. C. February	South African Museum.
Dr D.M. Avery	South African Museum.
Prof. T.C. Partridge	Transvaal Museum.
Mr D.B. Versfeld	CSIR FORESTEK.
Mr G.C. Schulze	S.A. Weather Bureau.
Prof P.D. Tyson	University Witwatersrand.
Mr P.K. Zawada	Council for Geoscience.

The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is acknowledged gratefully.

The main aim of the project has been to assess the potential for using stable carbon isotope ratios of wood charcoal as a climate indicator. To this end the project has been successful. This success would not, however, have been possible without the assistance and co-operation of many individuals and institutions.

The research was carried out in the Palaeobotany laboratory of the Earth Sciences Division at the South African Museum. Without the use of Museum facilities the project would not have been possible. For this I would like to thank the Director, Dr M. Cluver, and the head of the Division Dr R.M. Smith. I would also like to thank the Administration Division at the

Museum for all their help, in particular, I would like to thank Trevor Wadeley and Denise Nel.

The archaeological charcoal samples and radiocarbon dates from Mhlwazini Cave and Collingham Shelter were provided by Dr Aron Mazel of the Natal Museum. Throughout the project I have had the close co-operation of Dr Mazel. I would like to thank him for sharing his ideas with me and supplying me with both published and unpublished data.

The dendrochronology section of this project would not have been possible without the enthusiastic support of many members of the Laboratory of Tree Ring Research at the University of Arizona. For this I would like to thank the Director Dr Malcom Hughes. I would also like to thank Dr Steve Leavitt who initiated this co-operation and provided laboratory facilities for me at the Tree Ring Laboratory. Rex Adams supplied me with the *Widdringtonia* samples housed in Tucson and also taught me the basics of dendrochronology. Rex was always available when I needed him. Among others in the Tree Ring Laboratory I would like to thank in no particular order are Mark Kaib, Shelley Danzer, Martin Munro, Richard Holmes, Gregg Garfin, Bob Lofgren and Henri Grissino-Meyer.

An extant wood collection came from nature reserves and wildlife parks administered by the National Parks Board, Natal Parks Board, Cape Nature Conservation and Transvaal Administration, as well as from many private farms. For this I am grateful to Dr Richard Newberry of the Transvaal Provincial Administration, Dr W.P.D. Gertenbach of the National Parks Board, Dr O. Bourquin of the Natal Parks Board, Dr Guy Palmer, Nigel Wessels and SW van der Merwe of Cape Nature Conservation, the Alcocks of Mhlopeni Nature Reserve, David and Dorothy Green of the farm Rensburgspruit, Conrad Rocher of the farm Baviaanskrantz, Ed Hanisch and Dries Bester at the University of Venda, as well as many park wardens, game rangers and others.

The samples of yellowwood were specially cut for this project by Tinus Botha of Cape Nature Conservation and supplied to me by Dr Jeremy Midgely of the Department of Botany at the University of Cape Town.

Stable carbon isotope ratios as well as ring width measures were correlated with mean annual rainfall. These rainfall figures were obtained from the Weather Bureau (Dept of Environment affairs), the Computer Centre for Water Research, the National Parks Board, Transvaal

Provincial Administration and the Natal Parks Board. The co-operation of all of these bodies in this regard is gratefully acknowledged.

The *Eucalyptus* sample used in this project was originally grown not for this study but in an experiment designed to select for drought tolerant and productive *Eucalyptus* spp. by FORESTEK (D.R. de Wet Research station) in collaboration with the University of Cape Town. These samples were made available to the project through the co-operation of Debbie Le Roux, Dr W. Stock and Dr W. Bond of the Department of Botany at the University of Cape Town and Dirk Versfeld of FORESTEK.

The backbone of this project has been Noel Fouten, Marilyn Pether and Lesley Edmonds, who have between them sanded, microtomed, sectioned, labelled and measured hundreds of pieces of wood to enable us to arrive at the conclusions presented in this report. Nicky Allsopp and Colin Potts helped me with the field work while Rina Krynauw helped to obtain many interlibrary loans.

The stable carbon isotope analysis was carried out in the Archaeometry laboratory in the Archaeology Department of the University of Cape Town. I would like to thank all the people in the lab. for making my time spent there so pleasant. In this regard I would especially like to thank Stefan Woodbourne and John Lanham.

CHAPTER ONE

INTRODUCTION

Introduction

The emphasis of this study is on the evaluation of a new technique in climate reconstruction based on the stable carbon isotope ratios of charcoal excavated from archaeological sites. Incorporated within this objective is the reconstruction of the rainfall history of the last 300 years in the summer rainfall region of South Africa.

Rationale for this project

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The main aims of the project are:

a. To determine the stable carbon isotope ratios of contemporary wood samples across a climate gradient as well as across the diameter of a tree as a relative rainfall indicator.

b. Evaluate the stable carbon isotope ratios of charcoal from archaeological sites as a rainfall indicator.

c. Extend the rainfall record further back in time using the xylem anatomy of radiocarbon dated charcoal from archaeological sites.

d. Extend the results obtained from the xylem anatomy to the results obtained from stable carbon isotope ratios of the same assemblages.

e. Assess the dendrochronological potential of two South African woody species.

Charcoal identification and relative abundance

Much work has been done using wood charcoal from archaeological sites in the reconstruction of a woody environment. The pioneering work in this field is that of Salisbury and Jane (1940) and Godwin and Tansely (1941). Subsequently other workers have made contributions to the research field such as Hadac and Hasek (1949), Slavikova-Vesela (1950), Vernet, (1973) and Deacon (1979). The emphasis of these studies lay in a detailed study of environmental change through wood identification from xylem anatomy. The identification of wood to genus/species level is possible because the different genera have distinctive combinations of anatomical features visible under the microscope. Wood when charcoaled maintains its anatomical structure so that charcoal can also be identified by the characteristic arrangement of different cell types (Salisbury and Jane, 1940; Godwin and Tansley, 1941; Vernet, 1973; Kraus-Marguet, 1980).

Charcoal from archaeological sites represents the remains of firewood collected by people, who made specific choices on the types of wood they would use (Gandar, 1982; Milton and Bond, 1986). The archaeological record will, therefore, always be skewed in the direction of the favoured fuel wood, although environmental conditions will influence the species of wood available for collection. It is on this basis that environmental change can be inferred from changes in the charcoal record of archaeological sites.

In a recent project (February 1992, 1994a) a new technique for climate reconstruction was developed which utilises measurements of vessel size and frequency in the cross-sectional xylem anatomy of archaeological charcoal. In this study (February 1992, 1994a) the wood anatomy of a number of samples was analysed across a rainfall gradient in order to determine the relationship between vessel size, vessel frequency, and rainfall for *Protea roupelliae* and *Protea caffra*, two woody species endemic to the summer rainfall region of South Africa. The results indicate that for both wood and charcoal of these species, rainfall is correlated positively with xylem vessel size. On the basis of these results, an archaeological sample of P. *roupelliae* was analysed for changes in xylem vessel size through time as a means of determining past rainfall. The results suggest that in the Drakensberg rainfall may have been substantially higher in the past (ca. 1300 to ca. 1600 mm) than at present (ca 900 mm) (February 1992, 1994a).

Stable carbon isotope analysis

Once the charcoal from the archaeological sites has been identified, the project explores the potential for using stable carbon isotope measurements in tree rings and charcoal as a potential record of rainfall change through time. Recent studies suggest that plant $^{13}C/^{12}C$ ratios not only react to atmospheric CO_2 levels but are also good indicators of water available to plants (Freyer and Belacy, 1983; Leavitt and Long, 1986). These studies are based on the hypothesis that, when CO_2 is absorbed by plants the heavier ^{13}C isotope is discriminated against relative to the much lighter ^{12}C isotope due to diffusion during stomatal conductance and the kinetic effect of the chemical reaction as the CO_2 is absorbed by the enzyme RuBP carboxylase. With increased water stress, stomatal closure results in reduced CO_2 uptake and therefore less discrimination resulting in more positive stable carbon isotope values. Ehleringer and Cooper (1988) sampled various species along a moisture gradient in California and identified a change in $^{13}C/^{12}C$ ratios from -24‰ in the driest habitats to -26‰ in the wetter habitats. It is this relationship between stable carbon isotope ratios of wood and the amount of water available to the plant that is investigated here, in the rings of the same trees that were used by Dunwiddie and La Marche (1980) to establish their chronology from *Widdringtonia cedarbergensis*. This relationship is also investigated in the perspective of archaeological charcoal. In this respect, samples of wood and charcoal of both *Protea roupelliae* and *Combretum apiculatum* are analysed along a climate gradient.

Dendroclimatology

Dendrochronological age determination is necessary as a preliminary to determining the relationship between $^{13}C/^{12}C$ ratios of wood cellulose and rainfall across the diameter of a tree.

Within South Africa Dunwiddie and La Marche (1980) demonstrated the potential for using *Widdringtonia cedarbergensis* and Curtis, *et al.*, (1978) gave some evidence for the dendrochronological potential of *Podocarpus falcatus*. These initially promising results were however never fully exploited. The research outlined in this section of the project builds on and expands these earlier works.

In dendrochronology the age of a tree is precisely determined through an assignment of each consecutive annual ring to the year in which it is formed. Variations in the width of these rings forms the basis for cross-matching or cross-dating among specimens from the same locality. Ring width measures of a number of trees from the same locality which cross match precisely are combined to form a chronology. In dendroclimatology this chronology is related to available meteorological records to form the basis for climate reconstruction.

In this section of the project, the use of *Podocarpus falcatus* and *Podocarpus latifolius* in dendroclimatology is re-evaluated. The main aim, is to assess the potential for using these two *Podocarpus* species in dendrochronological cross dating and chronology development.

Dunwiddie and La Marche (1980) developed their tree ring chronology for a site in the Cedarberg mountains called Die Bos. Within this project I develop two new chronologies for cores and discs collected from a stand of known age trees at Algeria and Krakadouw. A comparison of the results for the two studies will be important in determining the contribution to climate research of ring width measurements using *Widdringtonia cedarbergensis*.

CHAPTER TWO

CLIMATE

Introduction

In general ambient temperature and water availability appear to be the most important climatic factors affecting plant growth and distribution. Through solar radiation ambient temperature provides the necessary energy for plant growth, while water availability determines the degree to which plants can meet evaporative and physiological demands posed by their particular structures (Box 1981). The pronounced seasonal nature of the rainfall in the summer rainfall region of South Africa means that within this region evaporation exceeds rainfall over a large part of the year. As a result, the plants live under water stress for most of the year indicating that rainfall is probably the most important influence on plant form and structure. In addition, Hall (1976) cites Gillooly (1975) as having determined a strong correlation between rainfall and growth increments of trees in the Rustenburg district of the Transvaal. Although the evidence is circumstantial it does support the argument that the major limitation on plant growth in the research area is rainfall rather than temperature. As a result, stable carbon isotope ratios of wood growing in this area should correlate with rainfall, rather than temperature.

It was also not possible to ascertain the extent to which stable carbon isotope ratios of wood cellulose and temperature correlate because the extant wood collection (more than 20 sites) was assembled from a number of nature reserves which do not collect temperature data but do have very good rainfall records.

Circulation patterns

The general feature of global atmospheric circulation is the tropospheric circumpolar westerly winds (Tyson 1986). Perturbations of these winds control daily weather. Within the southern Hemisphere these perturbations are derived from three semi-permanent high pressure cells: The South Atlantic anticyclone, the South Indian anticyclone and the East Pacific anticyclone. The main determinants of the climate of South Africa are the latitudinal position of the subcontinent which tapers from 20° to 35° S, the South Atlantic anticyclone the South Indian anticyclone and a region of pronounced convection activity where three major near surface air streams converge known as the inter-tropical convergence zone.

Figure 1 shows a simplified distribution of mean annual rainfall for southern Africa. The main feature of this rainfall is the general decrease moving westward from a maximum along the east coast and Drakensberg escarpment to a minimum along the west coast. Over almost the entire region rainfall maxima occur in summer. It is only in the south western Cape that there is a winter maximum of rainfall (Deacon and Lancaster 1988).

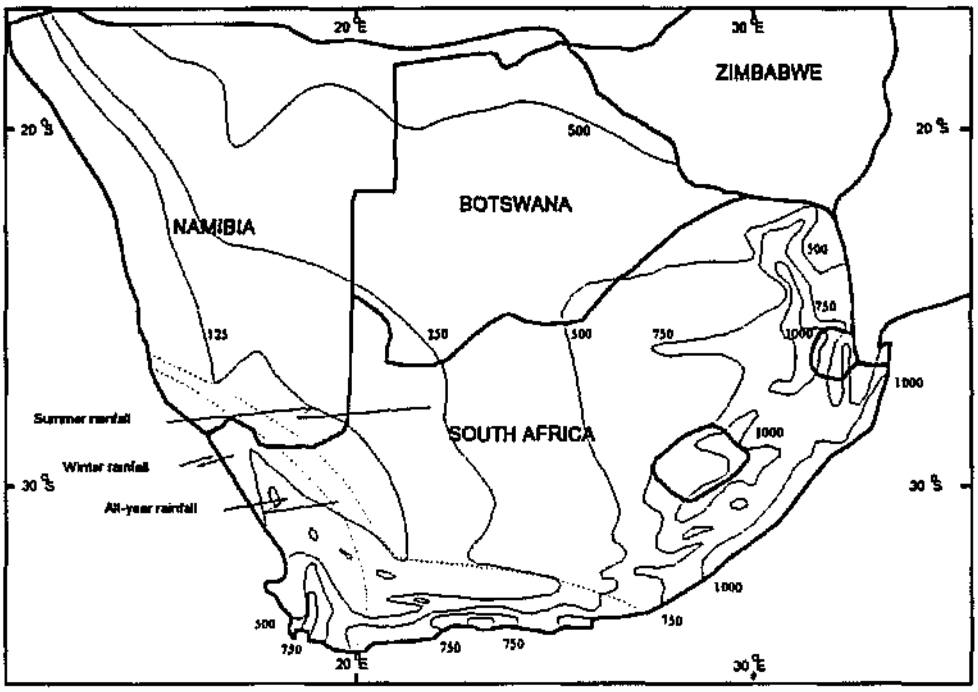

Figure 1. Mean annual rainfall for southern Africa (after Schultze 1972).

Wetter spells on the scale of days, seasons and years within the summer rainfall region are strongly influenced by a strengthening of the tropical easterlies as a result of the position of the inter-tropical convergence zone, which in summer lies just north of 20° S latitude, and a tropical low pressure cell located at 20° S latitude. This decrease in pressure over southern Africa is offset by an inverse in pressure over the south Atlantic as the South Atlantic anticyclone situated in the vicinity of Gough Island at this time of the year is strengthened. A result of this interaction between tropical easterly and temperate westerly circulations is the formation of north - west to south - east convergence zones and cloud bands. These cloud bands are the major source of summer rainfall and convective activity. At the same time, the westerlies and their associated storm tracts are displaced southwards resulting in a reduction of rainfall in the south westerly part of the country. During winter the tropical easterlies weaken with a displacement of the inter-tropical convergence zone northwards and a weakening of the South Atlantic anticyclone. A concomitant shift in the location of formation of interconnected tropical-temperate troughs and cloud bands occurs which results in a reduction in summer rainfall. In the south westerly part of the country, rainfall increases as the westerlies and their associated storm tracts are displaced northwards (Harrison 1986, Tyson, 1986).

Rainfall

Atmospheric circulation patterns are responsible for producing rain, the amount of rain is, however, strongly controlled by relief or distance from the warm Indian Ocean (Lilly 1977). The low-lying coastal regions of Natal and the Transkei have high but extremely varied mean annual rainfall ranging from 1000 mm (Newcastle) to 1600 mm (Umtamvuna). Mean values are however closer to 1000 mm with higher rainfall areas occurring in pockets such as at Gillits (1400 mm) and Tugela River Mouth (1200 mm). South of East London the mean drops to 750 mm. The interior lowlands have a much lower mean annual rainfall than the coastal lowlands as the affects of the Indian Ocean on the rainfall is lost. This area called arid savannah receives on average between 300 mm (Messina) and 600 mm (Phalaborwa). The interior lowlands is that area east of the Drakensberg escarpment, north of the Soutpansberg and east of Messina known as the lowveld. West of the Lowveld, the Drakensberg escarpment rises steeply for 800 - 1500 metres. This high mountain region extends southwards inland of the coast into the Cape Fold Belt mountains. The orographic effects of the Cape Fold Belt and the Drakensberg escarpment are very marked as this region has some of the highest rainfall figures for the country. The high mountain regions of the Wolkberg Nature Reserve in the Northern Province and Swartboskloof in the Cape receive a mean annual rainfall of 1600 mm but annual rainfall can exceed 2000 mm. To the west of the Lowveld, the Drakensberg escarpment falls off gradually to form the flat interior of the Transvaal known as the Highveld. Typical mean annual precipitation for this region are between 600 mm (Potgietersrus) and 650 mm (Nylsvley). Inland of the Cape fold belt and west of the Highveld lies the driest part of the country, the Karoo. Average annual rainfall for this region decreases from approximately 500 mm in the east to less than 100 mm over the north - western areas. Precipitation decreases progressively as one moves inland from the escarpment and east coast. The decline in amount of rain towards the interior and western sector of South Africa is associated with an increase in the unreliability of this rainfall.

CHAPTER THREE

CHARCOAL IDENTIFICATION AND RELATIVE ABUNDANCE AS AN INDICATOR OF VEGETATION CHANGE IN THE DRAKENSBERG.

Introduction

The primary objective of this project is to assess the potential for using stable carbon isotope ratios of wood charcoal from archaeological sites as a rainfall indicator. In order to meet this objective it is necessary to determine the stable carbon isotope ratios of a contemporary wood sample across a rainfall gradient so as to establish the relationship between rainfall and isotope variables for specific woody species. This section of the project serves to identify the most common woody species in the archaeological record so that the same species may be used for the modern transect.

A secondary goal of this section of the project is the interpretation of environmental conditions from wood identified by its xylem anatomy. Changes in the relative abundance of identified woody species in successive stratigraphic layers indicate changes in the vegetation mosaic and can thus provide biological evidence for climate change. This simple method for determining environmental change should give further information for palaeoclimatic and palaeoecological interpretation that is independent of and will clarify data obtained by other independent measures such as xylem and micro mammal analysis (February 1994a, Avery 1995) and palynology (Scott 1984). Although charcoal found in archaeological contexts reflects human selection as people made specific choices on the types of fuel wood they would use, past assemblages containing the relevant indicator species can provide much detailed climatic information (Prior and Price Williams 1985, Tusenius 1989, February 1992).

Methods

The research area from which archaeological samples were obtained is focused at Mhlwazini Cave (29°02'52":29°23'23") and Collingham Shelter(29°27'35":29°47'45") (Mazel 1990 & 1992). Both sites are located at an altitude of 1800 m in the Natal Drakensberg region of South Africa. These archaeological sites are cave sites situated in the main geological formation of the area, the Clarens Formation of the Karoo Sequence. Ecologically the Drakensberg area is Highland Sourveld which is a pure grassland on the more level parts but may form a *Protea* savannah on the slopes (Acocks 1953). It is the erosion of the Clarens Formation that forms the nutrient poor soils on which the main vegetation type, the *Protea* savannah belt, is located. Mhlwazini cave is on a small stream which flows into a tributary of the Mhlwazini River below Gatberg whereas Collingham Shelter is situated on a tributary of the Kwa Manzamnyama River which in turn flows into a tributary of the Inzinga. There is very little evidence for any woody vegetation in the vicinity of Collingham Shelter, whereas the mouth of Mhlwazini Cave is well screened by afromontane vegetation.

During the process of transpiration trees conduct water and dissolved minerals from the roots to the leaves via vessel and tracheids. Minerals and water can be stored in a separate group of less specialised cells (parenchyma) which are also depositories for waste material such as dissolved silicates. Trees and shrubs require mechanical support which is attained via yet another group of cells, the fibre cells. It is the characteristic arrangement of these various groups of cells in both horizontal and vertical planes that makes it possible to identify wood to genus or species level. Wood when charred retains this anatomical fingerprint so that wood charcoal can also be identified by the characteristic arrangement of the different cell types. An individuals fingerprints are unique only when compared with others. So too with wood. Archaeological charcoal samples can only be positively identified when compared with a charred reference collection which is obtained by sampling and charring the woody species growing in the vicinity of the archaeological sites today. Although not comprehensive, this collection consists of (in alphabetical order) *Bowkeria verticallata, Buddleja salviifolia, Combretum spinosum, Carissa bispinosa, Cliffortia nitidula, Diospyros whyteana, Erica sp., Euclea natalensis, Greyia sutherlandii, Halleria lucida, Ilex mitis, Leucosidea sericea, Maytenus heterophylla, Myrsine africana, Podocarpus latifolius, Protea caffra, Protea roupelliae, Rapanea melanophoes and Rhus tomentosa.*

In the laboratory discs approximately three centimetres in length were cut and wrapped in tinfoil. These parcels were placed in a muffle furnace, the temperature of which was gradually taken up to 400° C after 30 minutes after which the furnace was switched off and allowed to cool slowly. The resulting collection, along with the publication by Kromhout (1975) was used in the identification of the archaeological charcoal samples. Six assemblages of charcoal from Mhlwazini Cave and three from Collingham Shelter were chosen for analysis. Using 1 cm graph paper and computer generated random numbers sixty pieces of charcoal from each archaeological assemblage were randomly chosen for analysis. Both archaeological and extant samples were prepared for examination by physical fracture of each piece. A knife with a very fine serrated edge was used to make an incision perpendicular to the grain and through 360 degrees around the circumference of the piece of charcoal. The section was then snapped by placing the incision on a thumbnail and applying pressure with the left and right index fingers. The smoothest half of each section was mounted in "Prestik" on a glass slide. Once mounted the charcoal was ready for examination under a microscope. An inherent problem of fracturing charcoal for microscopy is that the prepared surface is rarely, if ever, absolutely flat. As incident light microscopes do not have the necessary depth of field to deal with an uneven surface a Nikon Optiphot M dark field reflected light microscope was used for identification purposes.

Results.

Results are satisfactory in that the most common wood types in the archaeological record could be grouped into generic types (Table 1 and Figure 2). Even though it is possible to separate *Diospyros* and *Euclea* on the basis of wood anatomic detail this was not felt to be necessary for the present study as the added resolution would not affect the interpretation in any way. In all, nine genera were identified and categorised in the various assemblages. A tenth and eleventh category was used for all wood not identified because of insufficient reference material and because of poor preservation. Of the 540 pieces of archaeological charcoal examined, 49 pieces or 9 % were not identified because of insufficient reference material. Of the rest, the preservation was such that only 17 pieces were unidentifiable owing to a lack of structural detail (Table 1 and Figure 2).

Table 1. Percentages of charcoal from Mhlwazini Cave and Collingham Shelter in the Natal Drakensberg.

Site	Mhlwa	Mhlwa	Mhlwa	Mhlwa	Mhlwa	Colling	Colling	Colling	Mhlwazini
Layer	LSFE F4	MBS D3	BSI E3	BS2 E3	WMAC E3	TBS P5	BSV2	BSV3	AOBS D3
Number of samples	60	60	60	60	60	60	60	60	60
^{14}C Date		190 ± 45		320 ± 40	580 ± 50	1260 ± 50	1800 ± 50	1880 ± 45	2280 ± 50
Laboratory Number		Pta 5102		Pta 4850	Pta 4864	Pta 5408	Pta 5096	Pta 5101	Pta 4868
Protea	20	23	27	35	23	80	87	63	37
Leucosidea	37	15	20	17	48	12	7	17	23
Podocarpus	7	13	5	30	2	0	0	0	2
Euclea/Diospyros	13	22	8	2	10	0	0	0	15
Maytinus	2	2	5	0	2	0	0	0	0
Ilex	5	0	5	3	0	0	0	0	0
Bowkeria	2	13	5	2	2	0	0	0	0
Rhus	2	0	3	5	0	0	2	0	0
Erica	3	0	0	0	0	3	2	7	0
unidentified	5	12	17	5	7	5	0	10	22
unidentifiable	5	0	5	2	7	0	3	3	2

The most common woody species represented in the charcoal from both archaeological sites is *Protea* sp. The percentages of *Protea* species in the charcoal from Mhlwazini Cave do not drop below 20%. At Collingham Shelter these percentages are much higher with the lowest percentage at 63%. There is an inverse relationship between the percentages of *Leucosidea* and *Protea*. The *Euclea/Diospyros* sample also shows some inverse trends to *Protea* but this is not as definitive as that exhibited by *Leucosidea*. The diversity of genera brought to the archaeological sites as firewood, increases towards the present although this diversity remains much lower at Collingham Shelter than at Mhlwazini Cave (Table 1 and Figure 2).

Discussion

The genus *Protea* has a wide distribution range throughout Africa with, according to Rourke (1980), 13 species in the summer rainfall region of South Africa. Only two of these species occur at Mhlwazini Cave today. On a collecting trip to the area in 1993 one specimen of *P. caffra* and about ten *P. roupelliae* were growing within a 2 km radius of the shelter. Most specimens growing in the area were mature plants growing in the more sheltered habitats amongst rocks or on very shallow soils. The vegetation at Mhlwazini Cave differs from that of Collingham Shelter in that there is a high percentage of forest margin and precursor shrub forest on the talus slope in the mouth of and for a short distance along the stream bank in

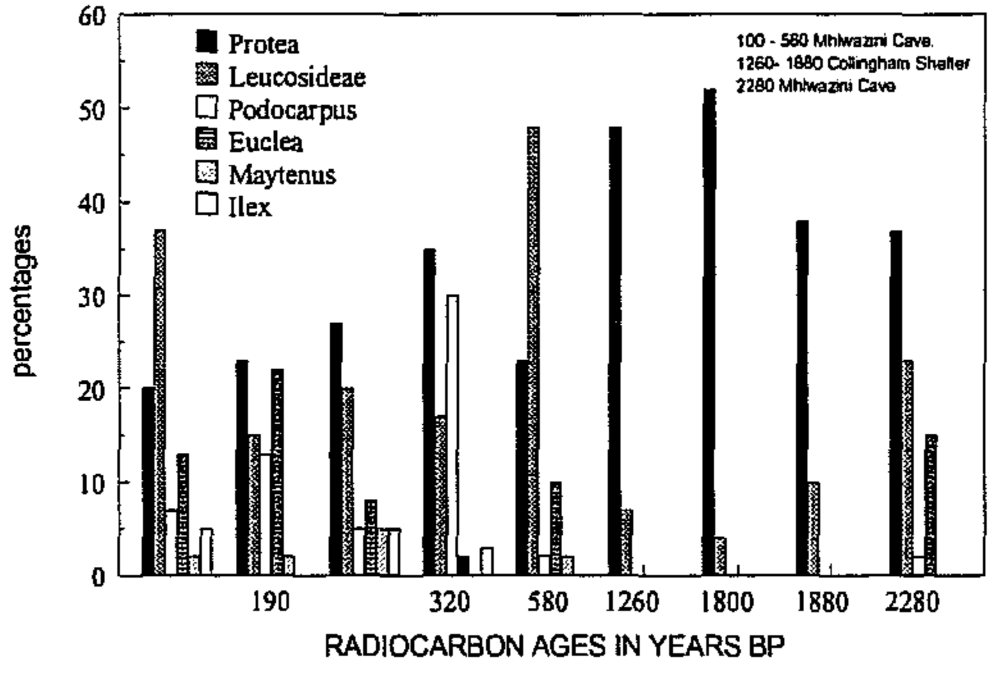

Figure 2. Percentages of the most common woody species identified in the charcoal from Mhlwazini Cave and Collingham Shelter

front of the Cave. At Mhlwazini Cave today, the amount of dry wood available from this source far exceeds that available from the few *Protea* specimens in the area. This suggests that the decline in *Proteas* has continued over the past 100 years even though Mhlwazini Cave is in a Nature reserve.

It has been suggested that changes in the relative abundance of woody species represented in the archaeological record result at least partly from human selection in firewood procurement (Prior and Price Williams 1985, February 1992). According to studies on firewood procurement strategies of contemporary subsistence farmers, people are very specific about the types of woody species they select as fuel wood (Gander, 1982, Milton and Bond, 1986). The preference for certain fuel woods over others is linked to the local availability of particular species as well as size, shape, wood hardness and the presence or absence of thorns (Eberhard and Poynton, 1987). Other species are avoided for various reasons including superstition (Gandar, 1982). Thus high percentages of *Protea* and *Leucosideae* in the archaeological record compared to percentages in the modern environment may be linked to human selection in firewood procurement. Despite this apparent bias, past assemblages containing specific indicator species whose ecological susceptibilities are well understood can provide much detailed climatic information (Prior and Price Willliams 1985). *Protea roupelliae* grows over a wide range in rainfall from 765 mm at Suikerbosrand to 1664 mm at Umtamvuna. Within this rainfall gradient there is however a wide range in the number of available specimens. There are very few specimens growing at the lower end of the rainfall distribution for this species (Suikerbosrand 760 mm) whereas there are large colonies in the higher rainfall areas such as at Gillits (1400 mm) and Umtamvuna (1600 mm). Estimated rainfall for Mhlwazini Cave today is about 850 mm. It is therefore possible that rainfall in the area of Mhlwazini Cave has declined through time and this is manifested in the decline in percentages of *Protea* brought into the Cave by people as availability of these plants declined with the decrease in rainfall.

It is, however, more likely, that the decline in the *Protea* savannah of the Drakensberg is linked to people rather than climate. The decrease is most evident over the last 300 years as farming intensity in the area increased. This decline in the *Protea* savannah is probably caused by an increase in the number of veld fires in the area surrounding the archaeological sites rather than a decrease in rainfall. At Collingham Shelter the difference between the contemporary environment and the archaeological record is even more striking than at Mhlwazini Cave. Before sedentary farmers first moved into the area more than 60% of the charcoal sample can be identified as *Protea* species. Collingham Shelter is on a private farm managed purely as a cattle ranch. Today there are no *Proteas* growing in the immediate vicinity of the archaeological site probably because annual burning is used to enhance the quality of the grazing. Hluhluwe Game Reserve has a serious bush encroachment problem as a result of which management has been forced towards burning programmes which are specifically designed to counteract this. The result is that there is no *P. roupelliae* in evidence in the reserve today even though Rourke (1980) mentions the Hlabisa area of the Hluhluwe Game Reserve as having the most northerly coastal population of this species.

The suggestion is that rather than climate change, it is people that have had the greatest impact on the environment in the vicinity of the archaeological sites of Mhlwazini Cave and Collingham Shelter. Edwards (1967) examined a number of dead or dying *Proteas* and concluded that the most common cause of death could be ascribed to a marked increase in veld burning as the result of increases in population and settlement of the Tugela basin over the last 100 years. The present evidence indicates that this process began at least 400 years ago when agriculturists first moved into the area.

Conclusions

The main aim of this section of the project was to identify the woody species evident in the archaeological record from Collingham Shelter and Mhlwazini Cave. In this regard, this section of the project has been successful in that the most common woody species represented in the charcoal from both archaeological sites has been identified as *Protea*. As *Protea roupelliae* is more common than *Protea caffra* in the vicinity of these sites it is probably this species that is represented in the archaeological charcoal record.

The results of the charcoal identification does not, however, show any vegetation change which can be attributed to climate. The evidence presented here suggests that in this area of the Drakensberg there should be a higher percentage of *Protea* savannah than what is evident in the area today. It would appear that this decline in *Protea* in the Drakensberg Mountains is not linked to a decrease in rainfall over the last 400 years. Rather, the decline can be related to present burning programmes which are designed to maintain open grassland communities.

CHAPTER FOUR

AN ASSESSMENT OF THE DENDROCHRONOLOGICAL POTENTIAL OF TWO *PODOCARPUS* SPECIES.

Introduction

In the previous Chapter *Protea roupelliae* is identified as the major woody species in the archaeological record from both Collingham Shelter and Mhlwazini Cave in the Drakensberg Mountains. Based on this identification *P. roupelliae* is used later in this study (Chapter 7) to determine the relationship between stable carbon isotope ratios of contemporary wood samples and climate. This species does not, however, form clearly defined annual rings so cannot be used to determine the relationship between stable carbon isotope ratios and rainfall across the diameter of a tree. For this type of analysis dendrochronological age determination is necessary. The following two Chapters (3 and 4) describe an assessment of the dendrochronological potential of two *Podocarpus* species and *Widdringtonia cedarbergensis* prior to stable isotope analysis of the rings across the diameter of a tree.

Dendrochronology in the northern hemisphere provides a good climate record going back in time for thousands of years (Ferguson 1969, Hillam *et al.*, 1990) but of the vast number of tree species existent in South Africa, few have dendrochronological potential. Lilly's (1977) assessment of 108 indigenous South African trees identified the *Podocarpus* and *Widdringtonia* species as having potential for dendrochronology. It was this research effort along with that described by Hall (1976) for a single *Podocarpus falcatus* specimen from Karkloof in Kwazulu/Natal that directed the focus for tree ring research in South Africa on *Podocarpus* and *Widdringtonia* species (McNaughton *1978*, Curtis *et al.*, *1978*, McNaughton and Tyson 1979, Dunwiddie and Le Marche 1980, Tyson 1986).

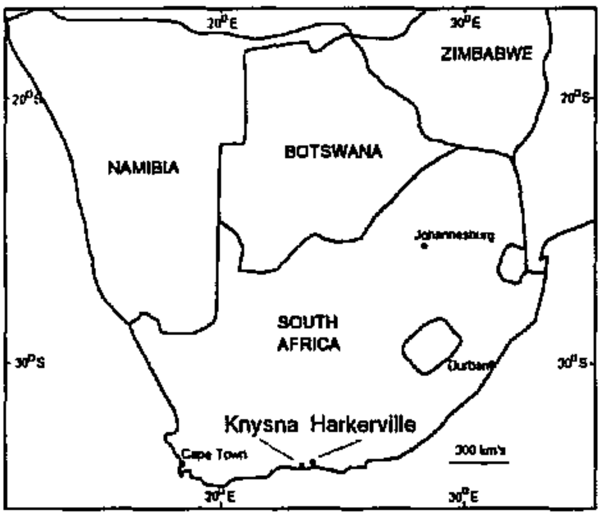

Figure 3. Map showing the location from which samples of *P. falcatus* and *P. latifolius* were collected

Dendrochronology is based on the principle that a tree grows both apically and radially each growing season; and, that this growth results in the formation of an annual ring (Ferguson 1970). This, however, is not a biological certainty as previous research (Curtis *et al.*, 1978) has indicated that ring counts in *Podocarpus* do not always correspond to the age of the tree because of the tendency for rings to merge and show discontinuities. They (Curtis *et al.*, 1978) point out that only by felling the tree and working with whole trunk cross sections is age determination based on growth ring analysis feasible. No dendrochronological study using South African *Podocarpus* species moves beyond the work of Curtis *et al.*, (1978). McNaughton and Tyson (1978) using Curtis *et al's.*, (1978) methods do make some statements on climate from 12 trees from the Witelsbos forest in the southern Cape. There is, however, no mention in this study of either developing a chronology or of cross dating the trees.

Using fourteen trees of known age this section of the project re-evaluates the methods of Curtis *et al.*, (1978) while also examining the potential for using ring width measures of *Podocarpus* in the two fundamentals of dendrochronology; cross dating and chronology development.

Methods

Eight whole trunk cross sections of *P. latifolius* and six of *P. falcatus* were obtained from trees located at 340m elevation at Harkerville (34°03'S, 23°14' E) near Knysna on the south coast of South Africa (Figure 3). Age of the trees was determined by counting branch whorls, an accepted method used by the local foresters to date young *Podocarpus* trees. The trees were growing on deep, well drained soils derived from stabilised but unconsolidated dune sands comprising medium to coarse, well sorted quartz grains. Rainfall is non-seasonal with average annual receipts between 700-800 mm. Specimens were felled as close to the ground as possible so that the maximum possible age of the trees could be incorporated into the cross section. The initial sample size here is much smaller than the 20 or more trees recommended by Fritts (1976). This was, however, the maximum number of trees that we could rationalise cutting down as *Podocarpus* are rare and endangered.

In the laboratory, a belt sander (Makita 4" Japan) was used to prepare the specimens for microscopy starting with 60 grit paper and using progressively finer paper finally finishing with 400 grit. Ages of the trees were then determined using the technique advanced by Curtis *et al.*, (1978) *i.e.* the circumference of each ring was traced as carefully as possible using a Wild M3C stereo microscope. After the ages were determined ring widths were measured on two radii of each section using a Wild M3C stereo microscope linked to the computerised image analysis programme FIPS (CSIR Pretoria). After manual cross-dating, the computer programme COFECHA (Holmes, 1983) was used to identify problems in measurement and to verify cross-dating. This programme allows for computer assisted quality control of the dating and measurements of the original indices. The software develops a master dating series and then compares each individual tree ring measurement index to that series.

Results

Percentage error between known age and ring count age for both *P. latifolius* and *P. falcatus* were much higher than expected ranging from 0% to 25% (Table 2). The ring structure of only one specimen was such that no estimate of age could be arrived at. One other tree has a very high percentage error (54%) which may be attributed to an error in whorl count. Of the eight samples of *P. falcatus* and six of *P. latifolius* examined, it was only possible to determine a pattern of wide and narrow rings common to two radii (cross-date) from one *P. falcatus* (number 2618, Table 2) and one *P. latifolius* (number 2625, Table 2) with any degree of certainty. It was not possible to cross date any of the other trees within themselves. Cross-dating of the 28 radii from 14 trees was not possible either among specimens of the same species or between species. Using the computer programme COFECHA (Holmes, 1983) as an aid to cross-dating did not improve the results.

Spec. num.	Height (m)	Age (years)	Age (rings)	% error
P. latifolius				
2620	1.5	14	18	22.2
2617	2.6	18	24	25
2615	2.1	19	24	20.8
2619	2.1	21	23	8.7
2613	2.7	23	24	4.2
2618	2.1	25	33	24.24
2614	2.8	26	30	13.3
2616	2.6	26	32	18.8
P. falcatus				
2624	1.2	12	26	53.84
2621	1.3	15	12	20.00
2623	2.2	19	16	15.78
2622	2.5	23	24	4.16
2626	3.0	23	23	0
2625	3.1	29	24	17.24

Table 2. Ring count results for *P. latifolius* and *P. falcatus.*

Discussion

Basic to dendrochronology is that each consecutive annual ring is assigned to the year in which it was formed. Inward from the precisely dated outermost ring successive growth rings are assigned to sequential years. Variations in the width of these rings due to climatic factors forms the basis for cross-matching or cross-dating among specimens from the same locality.

Marker years with exceptional divergence in ring width are matched up within a tree and between trees to corroborate the initial dating. After cross-dating the ring width measures of a number of specimens from the same locality exhibiting the same patterns in the width of these rings are combined to develop a chronology. In dendroclimatology this chronology is related to available regional temperature and precipitation records to form the basis for climate reconstruction.

In this section of the report an attempt is made, using *Podocarpus falcatus* and *Podocarpus latifolius*, to determine a methodology for dating, cross dating and chronology development, all of which are fundamental to dendrochronology and climate reconstruction from tree rings (Fritts, 1976). The results indicate that even though whole trunk cross sections were used, as advocated by Curtis *et al.*, (1978), there is still a large percentage of error when calculating age of these trees from ring counts. Furthermore, even if this percentage error were smaller a combination of poorly defined, locally absent and converging rings makes cross-dating between different trees from the same locality an impossible task. Cross dating within the same tree was almost as difficult only being possible in one *P. falcatus* and one *P. latifolius*. These results suggest that because of locally absent and converging rings future dendrochronological research using *Podocarpus* from the wetter parts of South Africa is not justifiable, especially since whole trunk cross sections have to be used in the analysis and *Podocarpus* are rare and endangered. It is possible that trees obtained from a dryer environment such as the north-eastern Transvaal or the west coast of South Africa may exhibit some attributes which can be used in chronology development. Any future research should focus on cross dating and chronology development from trees collected from the drier parts of South Africa as it has been shown that in the drier areas, where moisture stress is greatest, the climate signal within the ring series is enhanced (Fritts, 1967).

Conclusion

For too long now, the focus for dendrochronology in South Africa has been on *Podocarpus falcatus* or *Podocarpus latifolius*. The results of the present study indicate that this position is untenable. Dendrochronological research in South Africa should not focus solely on *Podocarpus* species, but should diversify, developing new methods and ideas with new species.

CHAPTER FIVE

THE RELATIONSHIP BETWEEN RING WIDTH MEASURES AND PRECIPITATION FOR *WIDDRINGTONIA CEDARBERGENSIS* (CLANWILLIAM CEDAR).

Introduction

Compared to available instrumental and historical climate records of the northern hemisphere, the southern hemisphere has very few, and South Africa no high resolution climate series that extends back in time for more than 100 years. Tree ring records from South America have proved useful for almost 4000 years of temperature and precipitation reconstruction (Lara and Villalaba 1993) and similar results have been recorded from Tasmania (Cooke *et al.*, 1992) and New Zealand (Norton *et al.*, 1989). South Africa, however, presents more problems in the application of dendrochronological studies than any other region in the Southern Hemisphere. These problems have been dealt with extensively in the publications of the Climatology Research Group at the University of Witwatersrand (Lilly, 1977; Curtis *et al.*, 1978; McNaughton and Tyson, 1979; Dyer, 1982 and Tyson, 1986). These publications show that the wood of *Podocarpus* exhibits extreme circuit variability which is manifested in gross variations in ring width around the circumference of the tree and in frequent wedging out of individual rings and groups of rings. Furthermore, this lack of circuit uniformity within *Podocarpus falcatus* and *Podocarpus latifolius* makes cross dating amongst specimens from the same location extremely difficult if not impossible (see Chapter 3). These problems suggest that dendrochronological research using *Podocarpus* species from South Africa is not justifiable especially since whole trunk cross sections have to be used in the analysis and *Podocarpus* are rare and endangered species (Dyer 1982).

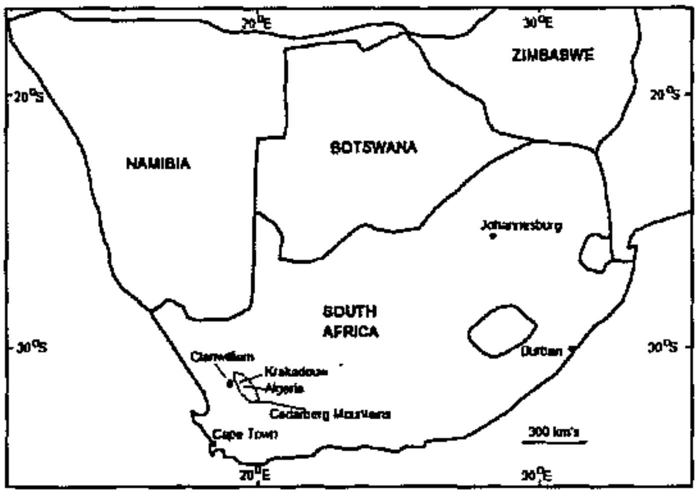

Figure 4. Map showing the location of the Cedarberg Mountains in South Africa and the sites from which samples of *Widdringtonia cedarbergensis* were collected.

The work of the Climatology Research Group has, however, focused dendrochronological research in South Africa on two species of *Podocarpus*. As a result of this research there has been very little progress in finding species that are more suitable for denrochronology. Dunwiddie and La Marche (1980) have successfully developed a chronology for *Widdringtonia cedarbergensis*. This chronology at a site called Die Bos, in the Cedarberg Mountains near Cape Town, is the only dated annual ring width chronology available for a South African indigenous species. However, Dunwiddie and La Marche (1980) were not able to establish a direct correlation between their ring width index chronology and rainfall or temperature. Rather, they could only tentatively interpret their chronology as a record of Spring and early Summer moisture availability. In a re-evaluation of the Dunwiddie and La Marche (1980) data set, Zucchini and Hiemstra, (1983) concluded that although significant at the 1 % level the correlation between the transformed ring width indices and rainfall records from the nearest weather station at Wupperthal were not sufficiently statistically significant to reconstruct rainfall patterns as only 22% of the variability in transformed ring width indices could be attributed to rainfall.

Following Zucchini and Hiemstra's (1983) conclusions that a rain gauge closer to the Die Bos site may well have resulted in a higher cross correlation, the research described in this paper uses *Widdringtonia cedarbergensis* from separate localities in the Cedarberg which were specifically chosen because of their proximity to rainfall stations. The results of the present study should therefore indicate whether a ring width index chronology of *Widdringtonia cedarbergensis* can be used in climate reconstruction.

Methods.

In accordance with the suggestion by Zucchini and Hiemstra (1983) the trees selected for this study are situated close to a rain gauge. Rainfall records for Algeria are available from 1900 to 1994 and are collected approximately 1500 m from the location of the trees. The nearest reasonable rainfall record to Krakadouw is located approximately 5 km away, at Wupperthal, with data available from 1898 to September 1977. These two data sets are ideally situated to explore more fully the relationship between ring width index chronologies of *Widdringtonia cedarbergensis* and rainfall.

Increment borer samples of *Widdringtonia cedarbergensis* were collected in February 1995 from 10 trees at Algeria (32° 22'S, 19° 04'E) in the southern Cedarberg and 12 trees at Krakadouw (32° 13'S, 19° 04'E) in the northern Cedarberg (Figure 4). At Algeria these samples were supplemented by a further 5 radial discs cut from living trees in May 1995 as well as 11 discs collected by La Marche and Dunwiddie in 1976 and 1978. We also collected radial cross sections from 9 trees killed in a fire at the Krakadouw site in January of 1995. The Algeria sample came from a plantation that had been planted circa 1910 at an altitude of 600 m in the southern Cedarberg, while the Krakadouw sample had been planted circa 1900 in the northern Cedarberg at an altitude of 1000m. The climate at these sites is classified as Mediterranean with definite winter rainfall between June and August of between 500 and 900 mm at Algeria and 200 to 300 mm at Krakadouw. The distance between the two sites, as the crow flies, is approximately 17 km. Clanwilliam which is approximately 26 km from Algeria and 15 km from Krakadouw at an altitude of 152 m has a mean maximum temperature of 27° C and minimum of 12°C.

In the laboratory a belt sander (4" Makita) was used to prepare the surface of the cores and discs for microscopy. Ring widths were measured with a computer linked (Bannister model) Henson incremental measurement machine in conjunction with a Bausch and Lomb stereoscopic microscope with cross hairs, normally at 15X to 30X magnification (Robinson and Evans 1980). Cross-dating following the technique described by Stokes and Smiley (1968) was extremely difficult and not always successful. As a result, a refinement on this technique was adopted, whereby rings were first measured and then cross dating was verified and corrected with the computer programme COFECHA (Holmes 1983). This programme allows for computer assisted quality control of the dating and measurements of the original indices. The software develops a master dating series and then compares each individual tree ring index to that series. All anomalies are then flagged so that these can be re-examined or re-measured to ascertain the nature of the problem.

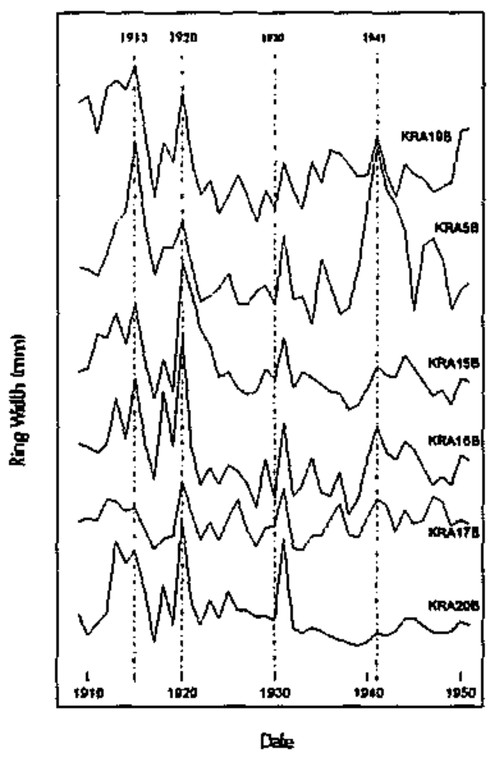

Figure 5. Portions of ring width plots for six trees from the Krakadouw site illustrating cross dating in the period 1910 - 1950.

Cross dated series were selected for high sensitivity and high correlation with the adjusted master series. The computer programme ARSTAN (Cooke 1985) was used to develop a chronology from each of the two localities. Ring widths were de trended into dimensionless indices to remove the effects of changes in tree growth that result from ageing as well as to homogenise the mean and variance and to produce a standard chronology for the site suitable for climate reconstruction (Cooke 1985). Climatic interpretation of the two chronologies was based on the relation between ring width indices and available regional precipitation records for the rainfall stations at Algeria and Wupperthal. These relations were investigated using correlation functions for various combinations of monthly and seasonal precipitation from 1919 to 1994 for Algeria and from 1898 to 1977 for Krakadouw.

Table 3. Tree-ring indices for Krakadouw.

Tree Ring Indices											Number of samples									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1896							1.39	0.18	1.55	0.90							1	1	2	4
1900	0.99	1.44	1.42	0.80	1.10	1.08	0.86	0.88	0.70	0.99	11	13	15	15	16	17	18	18	18	19
1910	0.84	0.96	1.11	1.40	1.11	1.61	0.99	0.54	1.02	0.70	19	19	19	19	19	19	19	19	19	20
1920	1.73	0.93	0.65	0.98	0.70	0.98	0.76	0.70	0.58	0.93	20	20	20	20	20	20	20	20	20	20
1930	0.73	1.73	0.64	0.64	0.78	0.64	0.66	0.66	0.53	0.55	20	20	20	20	20	20	20	20	20	20
1940	1.02	1.63	1.51	1.24	1.31	1.23	1.21	1.17	1.05	1.01	20	20	22	22	22	22	22	22	22	22
1950	1.52	1.59	1.30	1.43	1.59	1.37	1.23	1.19	0.86	1.04	22	22	22	22	22	22	22	22	22	22
1960	0.77	0.66	0.84	1.03	0.83	0.68	0.49	0.80	0.84	0.72	22	22	22	22	22	22	22	22	22	22
1970	0.69	0.69	1.07	0.69	0.96	0.82	1.20	1.03	0.81	0.87	22	22	22	22	22	22	22	22	22	22
1980	1.20	0.85	1.24	1.00	1.30	0.99	0.84	1.10	1.02	0.90	22	22	22	22	22	22	22	22	22	22
1990	1.25	1.12	1.07	1.16	0.94						22	22	22	21	21					

Table 4. Tree-ring indices for Algeria.

Tree Ring Indices											Number of samples									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1918									0.40	0.64									2	6
1920	0.43	0.56	0.66	0.95	1.07	0.92	0.93	0.86	0.87	0.75	6	7	7	7	9	11	19	19	19	19
1930	1.08	0.94	1.31	1.07	1.30	1.29	1.24	1.18	1.09	1.26	19	19	20	20	20	22	24	24	24	25
1940	1.11	1.13	1.29	1.13	1.06	0.87	0.67	1.08	1.10	1.07	25	25	25	25	25	25	25	25	25	25
1950	1.04	1.13	1.20	1.18	1.22	0.98	1.00	0.72	0.88	1.00	25	25	25	25	25	25	25	25	25	25
1960	1.03	0.98	1.14	1.45	1.25	1.15	1.04	0.69	0.92	1.23	25	25	25	25	25	25	25	25	25	25
1970	1.03	0.82	0.78	0.82	0.79	0.99	1.14	1.63	1.29	0.96	21	13	13	12	12	12	10	10	10	10
1980	0.88	1.08	0.79	0.84	0.75	1.00	0.91	1.08	1.32	1.10	10	10	10	10	10	10	10	10	10	10
1990	1.05	0.77	1.02	1.05	0.65						10	10	10	10	10					

Results

Of the 24 cores and 9 discs (21 trees) from Krakadouw only 22 radii (17 radii from discs and 5 from cores) from 11 trees were successfully cross dated (Figure 5). The oldest tree at Krakadouw was 99 years old which is very close to the approximate date of planting, 1898. Of the 16 Discs and 20 cores (26 trees) collected from Algeria only 25 radii (19 radii from discs and 6 from cores) from 14 trees were successfully cross dated. The oldest trees at Algeria date to 1918/1919. It is possible that about 4 years of growth are missing from the collected discs indicating a good correlation between actual age and ring count age.

Those samples which could not be cross dated were rejected because of several growth features which make cross dating in this species extremely difficult. Within the *Podocarpus* species lobate growth and especially wedging out of growth rings make cross dating an impossible task. These two features are not common in the *Widdringtonia*. What is, however common is a lack of definition of the end of the growing season which can often only be properly ascertained by carefully tracing the circumference of the ring on a cross section (Curtis, *et al.*, 1978). Cross dating is further complicated by false rings and resin filled bands of cells which are often more clearly defined than the actual growth ring. Ill defined termination of late wood growth is extremely common among the samples from Algeria, whilst being very rare in those samples from Krakadouw. This meant that it was possible to cross date all the discs (9) cut at Krakadouw while at Algeria 6 discs of a potential 16 did not cross date because of lack of definition in ring structure.

Using the computer programme ARSTAN (International Tree Ring Data Base) a chronology was built using 22 selected ring width series from 11 trees at Krakadouw (Table 3) and 25 series of 14 trees from Algeria (Table 4). These chronologies were correlated with rainfall figures from Algeria and Wupperthal. The results of the correlation coefficient analysis of average annual rainfall and ring width index chronology for Algeria shows that the trees at this site are less sensitive to rainfall ($R = 0.018$, NS) than those at Krakadouw ($R = 0.48$, $P<0.000$). There is a strong positive correlation between rainfall values from the two sites ($R = 0.75$, $P< 0.000$) with no significant correlation between ring width indices. The Krakadouw sample shows peaks in growth in Autumn and Spring with a definite decline during the hot dry months of February and March. Although the Algeria chronology is more complacent showing very little response to rainfall a similar pattern to that evident at Krakadouw is evident.

In their original analysis of the Die Bos chronology, Dunwiddie and La Marche (1980) found no significant correlation between ring width indices and combined climatological data from three stations (Clanwilliam, Calvinia and Langgewens). This led them to tentatively interpret their tree ring chronology from the Die Bos site as a record of spring and early summer moisture availability. The Die Bos site is in the rain shadow of the Cedarberg Mountains with much lower and more variable rainfall than at Clanwilliam and Langgewens. Using a closer rain gauge with a similar weather pattern at Wupperthal a correlation coefficient analysis of average rainfall and ring width index chronology for the Die Bos site does give a result which is statistically significant ($R = 0.36$, $P < 0.001$).

Discussion.

Unlike the many North American and European trees used for dendrochronology most South African woody species are not suitable for such purposes. Differing from the various *Podocarpus* species, circuit uniformity of *Widdringtonia cedarbergensis* is usually good, with lobate growth and wedging out of individual rings being uncommon. There is also a good approximation between age determination through ring counts and actual age of the trees. However, Dunwiddie and La Marche (1980) sampled 46 trees (58 cores and 25 discs) of these 32 trees (52 radii) make up their final chronology. This means that 30% of the trees sampled by them were found to be unsuitable for dendrochronological analysis. In the present study, 48% of the trees sampled at Krakadouw and 46 % of those sampled at Algeria were found to be unsuitable for analysis. The reasons for this is that many rings lack an abrupt termination of late wood growth and many have several false bands within the late wood, making determination of the precise ring boundary difficult. With discs it is often possible to trace the circumference of the ring, however, using cores this is not possible. As a result, only 21 % of the cores and 100% of the discs from Krakadouw and 30% of the cores and 62 % of the discs from Algeria were utilised in the final chronologies. These results indicate that although age determination of *Widdringtonia cedarbergensis* based on ring counts is possible a high percentage of the wood collected in the field will be unsuitable for dendrochronological purposes. *Widdringtonia cedarbergensis* is an endangered species. Cutting down trees for discs is not a viable option while it is only possible to cross date a very small percentage (20-30%) of all cores. The vegetation in which these trees grow is fire adapted. Trees killed in the regular fires that sweep the mountains can be used to provide the discs necessary for chronology development.

Rainfall in the Cedarberg Mountains is very variable with mean averages at Algeria (360 mm) being not only more consistent but also as much as three times higher than at Krakadouw (120 mm). The differences in rainfall at these sites are exhibited in the responses of the ring widths of the trees. At Krakadouw there is a much higher correlation between rainfall and ring width indices than at either Die Bos or Algeria. However, this response to rainfall only represents 23 % of the variation in ring width at Krakadouw and 13 % at Die Bos. While these correlations are significant, they are not sufficiently high for reconstruction of the rainfall record back through time (Zucchini and Hiemstra 1983).

Conclusions

This section of the study has shown that *Widdringtonia cedarbergensis* forms a new ring on an annual basis. Unlike the various *Podocarpus* species this ring is readily identifiable making dendrochronological age determination and cross dating possible. This species is therefore suitable for investigating the potential for using stable carbon isotope ratios of tree rings as a relative rainfall indicator.

CHAPTER SIX

A δ^{13}C CHRONOLOGY FROM TREE RINGS OF *WIDDRINGTONIA CEDARBERGENSIS* DURING THE 20TH CENTURY, CLIMATIC AND ENVIRONMENTAL IMPLICATIONS.

Introduction

The previous section of this project has indicated that unlike the various *Podocarpus* species dendrochronological age determination and cross dating is possible for *Widdringtonia cedarbergensis*. Recent climate and environment reconstructions have been based on stable carbon isotope ratios in tree rings (Peng and Freyer, 1986; Freyer and Belacy, 1983; Stuiver *et al.*, 1984; Leavitt and Long, 1988, 1989), C_4 plants (Marino and McElroy, 1991) and direct measures of air trapped in ice cores (Friedli *et al.*, 1986). The principal goal of this section of the project is to investigate the potential for using stable carbon isotope ratios ($^{13}C/^{12}C$) of wood cellulose from tree rings as an alternative method to ring width index analysis in climate reconstruction. Such reconstructions are based on the assumption that the ratio between the stable isotopes ^{13}C and ^{12}C can be a good estimate of water available to plants (Freyer and Belacy, 1983; Farquhar and Richards, 1984; Hubick *et al.*, 1986).

The main influence on stable carbon isotope values of cellulose in C_3 plants is the diffusion of CO_2 through the stomates. As atmospheric CO_2 is taken up by the plant during photosynthesis fractionation of the carbon isotope occurs due to the width of the stomatal pore and the heat generated during the chemical reaction as the CO_2 is absorbed by the enzyme RuBP carboxylase. The proportion of ^{12}C to ^{13}C can change because ^{12}C is slightly smaller and lighter than ^{13}C and thus reacts faster. Therefore, stomatal closure during periods of moisture deficiency should lead to elevated $^{13}C/^{12}C$ ratios as a reduction of available CO_2 during this period leads to diminished photosynthetic discrimination against the heavier ^{13}C isotope in favour of the lighter ^{12}C isotope (Francey and Farquhar, 1982). Ehleringer and Cooper (1988) sampled various species along a moisture gradient in California and identified a change in $^{13}C/^{12}C$ ratios from -24.2‰ in the driest habitats to -26.5‰ in wetter conditions. It is this relationship between carbon isotope values of wood cellulose across the diameter of a tree and the amount of water available to the tree on an annual basis that is the main focus of this section of the project.

Methods

In the south western Cape, Dunwiddie and La Marche (1980) report on the development and interpretation of an annual ring width index chronology of the Clanwilliam cedar (*Widdringtonia cedarbergensis*). The Dunwiddie and La Marche chronology was derived from 52 radii of a total of 32 trees from a site in the Cedarberg mountains near Cape Town called Die Bos (32° 24', 19° 13') at an elevation of 1330 m. The two cores from each of 6 of these trees with the highest correlations in ring width measures were taken for stable carbon isotope analysis. The individual rings from 1900 to 1977 were removed from the cores with a scalpel under a stereo microscope (Wild M3C - Switzerland). The annual rings from the six trees were then pooled to form a combined sample for each year to produce a site representative $^{13}C/^{12}C$ chronology. After milling, oils and resins were leached from the samples with toluene - ethanol in a soxhlet extractor and the cellulose was isolated by delignification at 70° C using acetic acid - acidified sodium chlorite solution (after Green 1963 and Leavitt and Danzer 1993).

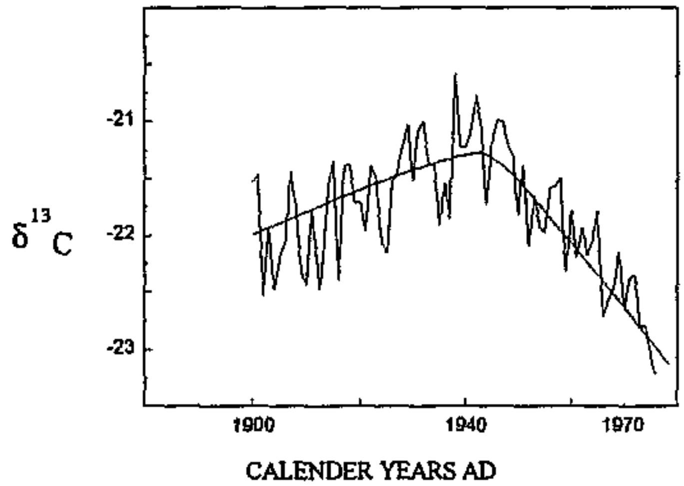

Figure 6. $\delta^{13}C$ values of *Widdringtonia cedarbergensis* from 1900 to 1977 showing the trend toward more negative values.

All stable carbon isotope analysis was done in the Archaeometry laboratory at the University of Cape Town. The sample (0.02 grams), copper oxide and a piece of silver foil were loaded into quartz tubes, the tubes evacuated to less than 10^{-2} Torr, sealed off with an oxy - butane torch and heated for a minimum of 4 hours at 800° C. The CO_2 produced was separated from any nitrogen and water on a cryogenic gas separation line (after Sealy 1986). Stable carbon isotope measures were carried out on a Micromass 602 E spectrometer. This is a 90° sector double collector instrument with dual inlet system. The carbon $^{13}C/^{12}C$ ratio of a sample relative to a standard is designated as $\delta^{13}C$. The universally accepted standard in carbon analysis is Peedee Belemnite (PDB) (Craig 1953, 1957). $\delta^{13}C$ values are calculated relative to this limestone from the equation:

$$\delta^{13}C = \left(\frac{^{13}C/^{12}C_{\text{sample}}}{^{13}C/^{12}C_{\text{standard}}} - 1\right) \quad X1000‰$$

Depletion or enrichment of ^{13}C is expressed in ppm (‰). Most organic materials are depleted in ^{13}C relative to PDB and therefore have negative values (Sealy 1986). The references were

DATE	*Widdringtonia* $\delta^{13}C$, ‰	Rainfall mm	Atmospheric. $\delta^{13}C$, ‰	DATE	*Widdringtonia* $\delta^{13}C$, ‰	Rainfall mm	Atmospheric. $\delta^{13}C$, ‰
1900	-21.51	329	-6.77	1939	-20.58	170.5	-6.87
1901	-21.53	264	-6.78	1940	-21.22	173.4	-6.85
1902	-21.45	374.1	-6.79	1941	-21.22	389.9	-6.84
1903	-22.53	231.7	-6.80	1942	-21.09	257.3	-6.83
1904	-21.95	378.8	-6.76	1943	-20.77	253.7	-6.82
1905	-22.48	308.6	-6.71	1944	-21.08	195	-6.82
1906	-22.21	268.2	-6.67	1945	-21.73	288.4	-6.83
1907	-22.04	186.5	-6.63	1946	-21.18	210.1	-6.83
1908	-21.43	174.3	-6.58	1947	-20.99	178.5	-6.83
1909	-21.76	363.4	-6.54	1948	-21	290.4	-6.84
1910	-22.35	237.9	-6.59	1949	-21.19	164.9	-6.84
1911	-22.44	180.9	-6.65	1950	-21.29	235.8	-6.84
1912	-21.78	206.9	-6.70	1951	-21.82	229.9	-6.84
1913	-23.05	267.9	-6.75	1952	-21.39	251.2	-6.85
1914	-22.23	354.2	-6.81	1953	-22.1	248.2	-6.85
1915	-21.55	393.4	-6.86	1954	-21.65	386.8	-6.83
1916	-21.34	307.7	-6.84	1955	-21.93	384	-6.81
1917	-22.41	259.2	-6.82	1956	-21.98	194.4	-6.79
1918	-21.39	324	-6.80	1957	-21.59	361.7	-6.83
1919	-21.37	150.7	-6.78	1958	-21.57	113.3	-6.87
1920	-21.71	360.2	-6.76	1959	-21.49	285.4	-6.90
1921	-21.71	435.9	-6.74	1960	-22.32	107.3	-6.94
1922	-21.97	214	-6.75	1961	-21.78	260.8	-6.98
1923	-21.39	204.8	-6.75	1962	-22.2	357.4	-7.02
1924	-21.5	155	-6.76	1963	-21.93	305.1	-7.06
1925	-22.05	355.7	-6.77	1964	-22.18	159	-7.09
1926	-22.16	117.7	-6.77	1965	-22.03	136	-7.13
1927	-21.53	137.3	-6.78	1966	-21.78	82	-7.17
1928	-21.44	76.5	-6.80	1967	-22.72	309.1	-7.20
1929	-21.22	246.1	-6.81	1968	-22.58	200	-7.24
1930	-21.03	195.7	-6.83	1969	-22.47	109.5	-7.27
1931	-21.53	193.5	-6.85	1970	-22.15	190.5	-7.31
1932	-21.08	203.6	-6.86	1971	-22.65	176.5	-7.34
1933	-21.00	240.6	-6.88	1972	-22.38	123.5	-7.38
1934	-21.37	190.7	-6.89	1973	-22.36	155.9	-7.41
1935	-21.39	252.3	-6.91	1974	-22.81	294.3	-7.45
1936	-21.92	236.6	-6.90	1975	-22.79	209.5	-7.48
1937	-21.54	200.7	-6.89	1976	-23.08	363.5	-7.52
1938	-21.85	126.2	-6.88	1977	-23.22	230.8	-7.55

Table 5. Stable carbon isotope results of *Widdringtonia cedarbergensis*, Wupperthal rainfall and an extrapolation of the $\delta^{13}C$ values of the atmosphere based on the Siple ice core results (Friedli *et al.*, 1986).

done against a laboratory gas related to the Chicago PDB marine carbonate standard by calibration against six NBS reference standards (see van der Merwe 1982 and Sealy 1986).

Results

The $\delta^{13}C$ chronology is plotted in Figure 6. $\delta^{13}C$ values decline from a plateau of -21.5‰ at 1900 to -22.5‰ at 1903 after which values become less negative to 1947 (-20.99‰) (Table 5, Figure 6). The most notable aspect of the curve is the long term trend increasing slightly to 1947 and then falling rapidly after this date (Figure 6). The difference in $\delta^{13}C$ values from 1900 to 1977 is 1.7‰. the difference from 1947 to 1977 is 2.2‰. Correlations of $\delta^{13}C$ and various combinations of monthly and annual rainfall are not significant. There is also no significant relationship between ring width index chronology (Chapter 4) and $\delta^{13}C$ values.

Discussion

The main aim of this section of the project was to develop an alternative to ring width measures of *Widdringtonia cedarbergensis* as a climate indicator. Direct correlations between the $\delta^{13}C$ chronology and rainfall from Wupperthal are, however, not significant. Tree rings are complex interactive rather than passive monitors of climate and environment. A number of authors have noted that $\delta^{13}C$ values of tree rings do not simply reflect environmental $\delta^{13}C$ values but may also be affected by atmospheric CO_2 concentration (Freyer 1986; Leavitt and Long 1986). An important aspect concerning the relationship between stable carbon isotope ratios of tree rings and climate is the need to determine and thus exclude the extent of the anthropogenic contribution to $\delta^{13}C$ values. The value of the pre-anthropogenic atmosphere was around -6‰ and fossil fuels have values around -25‰ (Wigley 1982). Increasing use of fossil fuels should therefore shift atmospheric $\delta^{13}C$ signatures to more negative values. Ambient atmospheric isotope values today are around -8‰. Trees using this depleted CO_2 are therefore not reliable recorders of environmental factors.

The original *Widdringtonia* $\delta^{13}C$ chronology was corrected for the human fossil fuel impact using atmospheric CO_2 data obtained from ice cores by Friedli *et al.*, (1986) and direct atmospheric measures by Keeling *et al.*, (1979). Correlations of various combinations of the rainfall record from Wupperthal and the de trended *Widdringtonia* $\delta^{13}C$ curve are, however, still not significant. Not only are there no significant correlations with rainfall, but wetter and dryer cycles within the 77 years of measurement are also not reflected.

What is reflected in the stable carbon isotope curve, is the downward trend in $\delta^{13}C$ values which can be directly related to the anthropogenic CO_2 contribution through industrial and vehicle exhaust fumes. This clear trend which differs from the flat trend in Tasmanian trees reported by Francey (1981) is very similar to that reported by Leavitt and Lara (1994) for *Fitzroya cupressoides* trees from southern Chile and for the ice core record reported by Friedli *et al.*, (1986). The main difference is that the *Fitzroya* and Siple ice core trend is toward more negative $\delta^{13}C$ values from 1900 to 1983 with a plateau between 1920 and 1950 whereas the *Widdringtonia* sample shows less negative $\delta^{13}C$ values from 1913 to 1943 (Figure 7). These results are not unusual, as many trees show constant or increasing values between 1920 and 1950 (Freyer and Belacy, 1983). The annual fluctuations of up to 1‰, however, are far to large to represent quick changes in global $\delta^{13}C$ values. The shifts are probably related to ecophysiological changes related to local climate or environment change.

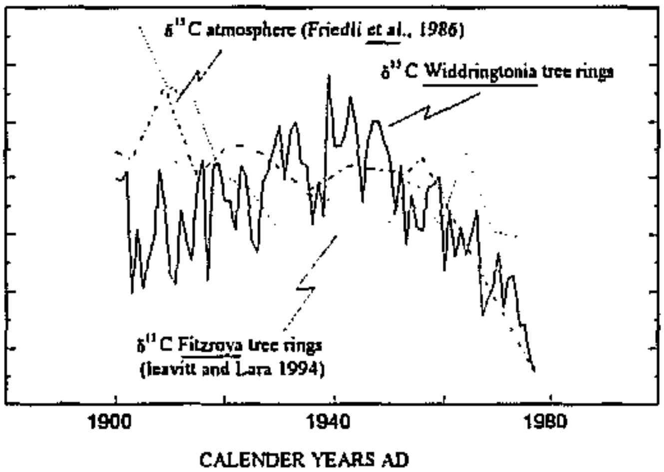

Figure 7. Comparison of the $\delta^{13}C$ trends from *Fitzroya* (Leavitt and Lara 1994), *Widdringtonia* and ice cores (Friedli *et al.*, 1986)

Conclusions.

The isotopic composition of wood cellulose from the growth rings of trees may document a record of $\delta^{13}C$ variations in atmospheric CO_2, represent physiological responses to environmental changes or a combination of both. The $\delta^{13}C$ record from the pooled trees at the Die Bos site does not correlate significantly with the rainfall record from Wupperthal. This correlation is not significant even when the *Widdringtonia* stable carbon isotope record is de trended for the anthropogenic CO_2 contribution. The *Widdringtonia* record does, however, indicate a strong correlation between stable carbon isotope ratios of tree rings and atmospheric carbon dioxide levels. This correlation is manifested by less negative $\delta^{13}C$ values from 1900 to 1947 and a clear decrease to 1977 which is very similar to that derived from ice core data (Friedli *et al.*, 1986) tree ring $\delta^{13}C$ chronologies from the northern hemisphere (Freyer and Belacy, 1983) and recent southern hemisphere records (Leavitt and Lara, 1994;

Figure 7). This is only the second chronology, and the first with annual resolution, to show a decline in $\delta^{13}C$ for the Southern Hemisphere. However, these results can only be substantiated by further stable carbon isotope work on tree rings not only from *Widdringtonia* but from other species in different parts of South Africa.

CHAPTER SEVEN

RELATIONSHIPS BETWEEN WATER CONSUMPTION, PLANT GROWTH AND STABLE CARBON ISOTOPE RATIOS IN *EUCALYPTUS GRANDIS* AND THE HYBRID *EUCALYPTUS GRANDIS X NITENS*.

Introduction

Rather than trace the anthropogenic contribution to atmospheric carbon dioxide, the principal goal of this project is to assess the potential for using stable carbon isotope ratios of wood and charcoal as a rainfall indicator. To meet this objective it is important to understand the relationship between rainfall and the stable carbon isotope ratio of wood cellulose. In the previous section of this project, however, I show that the $\delta^{13}C$ chronology developed from *Widdringtonia cedarbergensis* for a site in the Cedarberg Mountains near Cape Town is not significantly related to rainfall from a nearby rainfall station (Wupperthal). Rather than rainfall, the trend in the $\delta^{13}C$ chronology of *Widdringtonia* is related to the anthropogenic CO_2 contribution to atmospheric $\delta^{13}C$ values. Even when de trended for the human influence on atmospheric isotope values, the *Widdringtonia cedarbergensis* $\delta^{13}C$ chronology does not correlate significantly with the Wupperthal rainfall record.

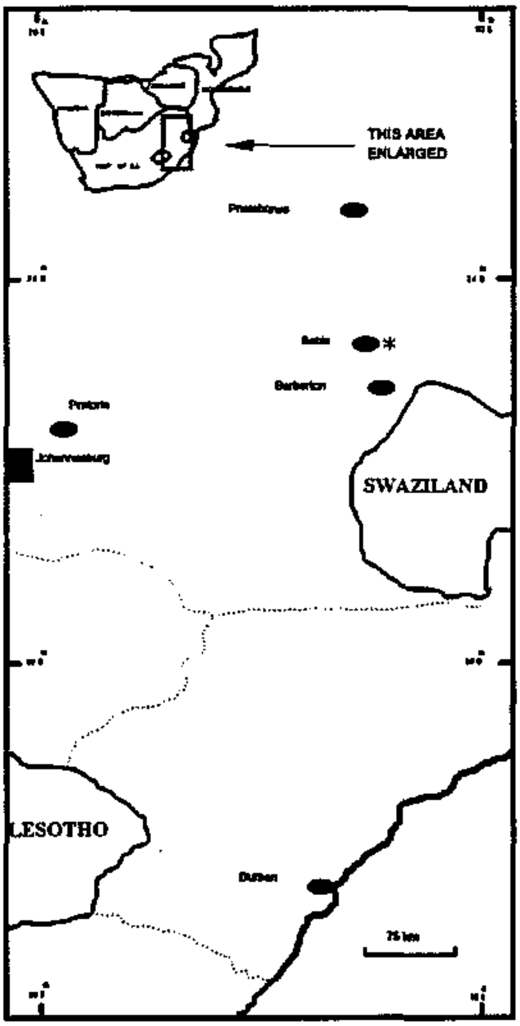

FIGURE 8 Map showing location of D.R. de Wet Research Station * in Mpumalanga.

However, recent studies suggest that plant $^{13}C/^{12}C$ ratios not only reflect atmospheric CO_2 levels but are also good indicators of water available to plants (Freyer and Belacy, 1983; Leavitt and Long, 1986). The basis of this assumption is that with increased water stress, stomatal closure results in reduced CO_2 uptake and therefore more positive $\delta^{13}C$ values. Ehleringer and Cooper (1988) sampled various species along a moisture gradient in California and identified a change in $\delta^{13}C$ values from -24.2‰ in the driest habitats to -26.5‰ in wetter conditions.

Lipp *et al* ., (1994) established a $\delta^{13}C$ chronology from tree rings of Spruce which showed significant correlations with the temperature, relative humidity and precipitation rates obtained at a nearby climate station for July and August.

There is therefore a definite need to experimentally ascertain what the relationship is between $\delta^{13}C$ values, wood cellulose and water consumption of trees. The primary objective of this section of the project was to determine under controlled conditions this relationship for *Eucalyptus grandis* and the hybrid *Eucalyptus grandis x nitens*. These trees were originally grown, not for this project but, in an experiment designed to select for drought tolerant and productive *Eucalyptus* spp by FORESTEK (D.R. de Wet Forestry Research Station; Figure 8) in collaboration with the University of Cape Town (Botany Dept).

A secondary objective of this section of the project was to investigate the association between stable carbon isotope values and the integrated measure of production per water used (Water Use Efficiency). *Eucalyptus* species, predominantly the Australian *Eucalyptus grandis* Hill ex Maiden, have been planted extensively in South Africa since the beginning of this century. The fast growth of *Eucalyptus* and the increased demand for wood and wood products in South Africa has meant a steady increase in the extent of these plantations despite the fact that *Eucalyptus* species consume large quantities of water (Henrici, 1946; Bosch and Von Gadow, 1990). Planting these trees in water catchment areas decreases water runoff to a wide area, thus reducing the agricultural viability of these areas. Selecting trees that use water more efficiently than currently exploited species/hybrids, without compromising production, is one possible solution to maintaining the viability of large agricultural districts in South Africa where rainfall is marginal (Henrici 1946). This consideration has meant that recent research has focused on the need to produce clones that use water more efficiently while still remaining productive. This emphasis has led to an increasing interest in the relationship between stable carbon isotope ratios and the integrated measure of production per water used (Bond and Stock, 1990; Olbrich *et al* ., 1993). As yet, the relationship between stable carbon isotope ratios and WUE has not been clearly established in trees. This relationship has, however, been established in crop plants where water stress results in some stomatal closure which results in reduced Ci/Ca (Internal leaf CO_2 concentration to atmospheric CO_2 concentration) and more positive $\delta^{13}C$ values (Farquhar and Richards, 1984; Hubick, et al., 1986). WUE_{sl} (Water use efficiency, season length, g/l) is calculated as the whole plant dry mass in grams divided by the amount of water used by the plant over the 16 month growth period.

Methods

On 21 March 1991 ten week old cuttings of *E. grandis* and the hybrid *E. grandis x nitens* were planted at 15 cm below soil surface in 220 litre drums, in the field, at the D.R. de Wet Forestry Research Centre (25° 3' 10", 30° 53' 30"; Figure 8). 3:2:1 NPK fertiliser (100g) and 2 litres of water were added to each drum at the time of planting. Rainfall was excluded from the drums by specifically adapted plastic sheets which allowed for the protrusion of the leaf stem and canopy. The drums were sunk in the soil with only the top 60 cm protruding to simulate, as closely as possible, actual growing conditions. Half of the individuals were subject to a low watering treatment and the remainder to a high treatment where soil moisture in the drum was maintained at 60 and 80 litres respectively. Soil moisture depletion through root uptake was measured each week with a neutron probe and the required amount of water used per plant was calculated over the 16 month growth period from when the cuttings were planted to when the plants were harvested (February *et al*., 1995). The pots were dug out by hand and the contents passed through a sieve of 10 mm mesh size to separate roots from soil. After being dried at 80° C for 48 hours each plant was weighed in order to calculate the whole plant dry mass in grams.

$\delta^{13}C$ values of whole leaf tissue and leaf cellulose become more negative with increasing distance from the base of the tree. In contrast to the behaviour of the leaves, however, the corresponding cellulose of the trunk does not show any significant $\delta^{13}C$ gradient (Leavitt and Long, 1986; Schleser, 1992). The reason for this is that the trunk carbon is composed of carbon fixed by all the leaves during photosynthesis (Schleser, 1994). Despite these assurances and as a control for possible variation only the main stem wood between ± 50 mm and ± 110 mm above the soil was analysed. A further control for possible variation in $\delta^{13}C$ values across the diameter of the stem was made by analysing a standard section of the secondary xylem 1 - 2 mm in towards the pith from the cambium.

Stem diameters, excluding the bark were measured at the widest point using dial callipers after which the transverse sectional area of the stem was measured and calculated using a binocular microscope (Wild - Switzerland) and the image analysing programme FIPS from the CSIR Pretoria. After measurement, the wood was prepared for stable carbon isotope analysis as described in Chapter 4. Samples were milled, after which oils and resins were leached out in a soxhlet extractor and the cellulose isolated by delignification (after Green, 1963 and Leavitt and Danzer, 1992). All stable carbon isotope analysis was done in the Archaeometry laboratory at the University of Cape Town and stable carbon isotope measures

	Variable	*Watering treatment*				
		Dry	*Std Dev*	*Wet*	*Std Dev*	*t test*
grandis						
	Nº of plants	11		14		
	Plant mass (g)	1107	233	2055	415	****
	Stem diameter (mm)	21	1	26	2	****
	Stem area (cm^2)	3.4	0.35	5.3	0.72	****
	Water uptake (l)	349	75	723	130	****
	Height (m)	1.72	0.10	2.08	0.21	****
	Nº of plants	9		14		
	δ13C, ‰	-22.5	0.45	-24.5	1.03	****
grandis x nitens						
	Nº of plants	8		9		
	Plant mass (g)	944	203	1900	267	****
	Stem diameter (mm)	19	2	27	3	****
	Stem area (cm^2)	2.9	0.6	5.5	1	****
	Water uptake (l)	252	41	631	113	****
	Height (m)	1.75	0.18	2.19	0.13	****
	Nº of plants	7		9		
	δ13C, ‰	-22.5	0.65	-23.5	0.72	**

Table 6. The differences between plant growth and δ13C values of *Eucalyptus grandis* and *E. grandis x nitens* after cultivation under different watering treatments. Values are means for the number of plants indicated. NS denotes no significant difference between means and *, **, ***, **** indicate significant difference between means at P< 0.05, 0.01, 0.001 and 0.0001 respectively.

were done on a Micromass 602 E spectrometer. References were taken against a laboratory gas related to the Chicago PDB marine limestone standard by calibration against six NBS reference standards (see van der Merwe 1982 and Sealy 1986).

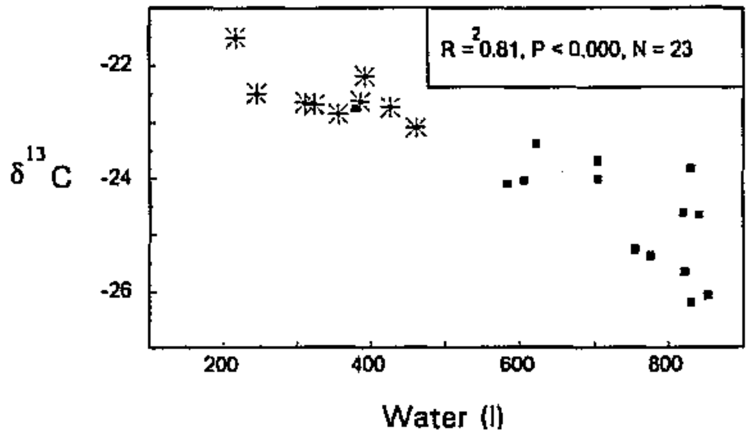

Figure 9. Relationship between $\delta^{13}C$ values and water consumption for *Eucalyptus grandis* in wet ▪ and dry ✳ treatments

Results

For both taxa water availability had a significant effect on mean total water consumed ($P< 0.001$) which in turn had a significant influence on stem diameter ($P < 0.0001$), Plant mass ($P < 0.0001$) and transverse sectional stem area ($P < 0.0001$; Table 6). In both taxa $\delta^{13}C$ values are significantly correlated to water used and plant mass (Figs. 9-12). There are, however no significant correlations between WUE_{sl} for both *Eucalyptus* species and stable carbon isotope values.

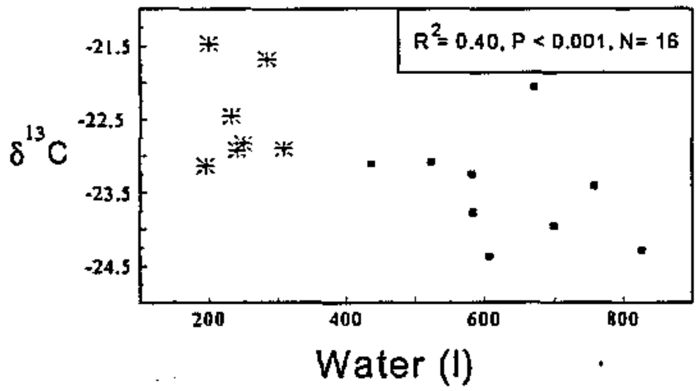

Figure 10. Relationship between $\delta^{13}C$ values and water consumption for *Eucalyptus grandis x nitens* in wet ▪ and dry ✳ treatments

Discussion

The primary objective of this section of the project was to determine under controlled conditions the relationship between $\delta^{13}C$ values, wood cellulose and water consumption of trees. The results of the experiments indicate that for *Eucalyptus grandis* and the hybrid *Eucalyptus grandis x nitens* carbon isotope ratios became more negative in the wet treatment. Carbon isotope ratios also became more negative as water consumption increased. Isotope values for *E. grandis* are more negative, with more significant correlations than *E. grandis x nitens.* The trend, however, clearly indicates that $\delta^{13}C$ values become less negative and plant biomass decreases as water consumption decreases.

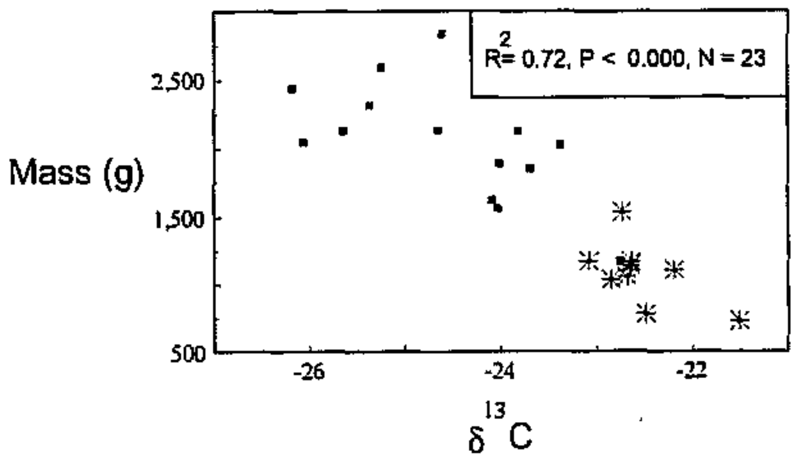

Figure 11. Relationship between $\delta^{13}C$ values and plant biomass in grams for *Eucalyptus grandis* in wet ▪ and dry ✳ treatments.

Differences between the wet and dry treatments also clearly indicate that with increased water stress, stomatal closure results in reduced CO_2 uptake and therefore more positive $\delta^{13}C$ values.

There is no significant correlation between WUE_{sl} for both *Eucalyptus* species and stable carbon isotope values. Rather, there are significant correlations between plant biomass (g), water consumption (l) and $\delta^{13}C$ values (Figs. 9-12). There are also significant correlations between water consumption and plant biomass ($P<0.0001$). This means that the *Eucalyptus* trees in this study are using more water to produce more biomass. As $\delta^{13}C$ values become more negative, the plant produces more biomass while using more water. If this is the case then for *Eucalyptus* trees, the determination of WUE_{sl} cannot be calculated by dividing the biomass by the amount of water used. This does not result in a ratio that can be meaningfully correlated with $\delta^{13}C$ values. For the two *Eucalyptus* species in this study, less negative $\delta^{13}C$ values mean low biomass and low water consumption but not necessarily high WUE_{sl}.

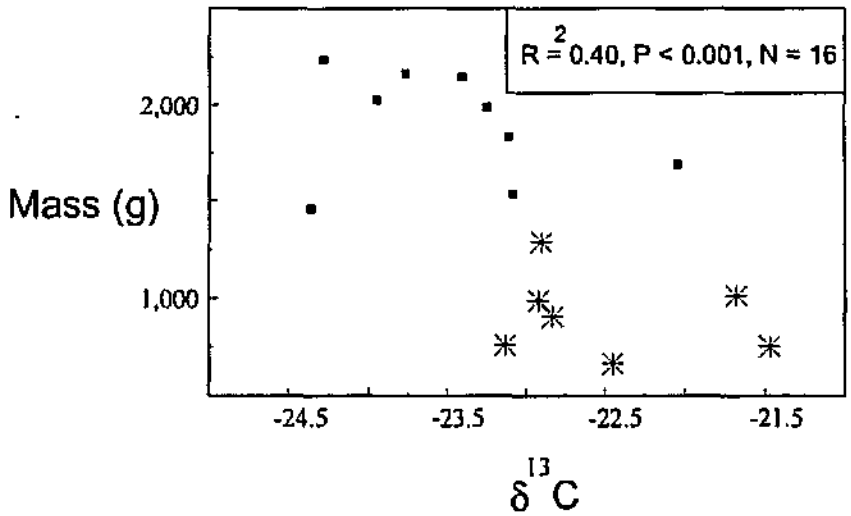

Figure 12. Relationship between $\delta^{13}C$ values and plant biomass in grams for *Eucalyptus grandis x nitens* in wet ▪ and dry ✳ treatments.

Conclusion

The main aim of this section of the project was to assess the relationship between $\delta^{13}C$ values of wood cellulose and the amount of water available to the tree. The results indicate that $\delta^{13}C$ values of both species of *Eucalyptus* become less negative as plant biomass decreases with a decrease in water consumption. These results suggest that the $\delta^{13}C$ values of tree wood cellulose may be useful in rainfall reconstructions, provided that the trees chosen for analysis are sensitive to changes in rainfall and that atmospheric isotope correlations are understood (see Chapter 4 and 5).

$\delta^{13}C$ values of *Eucalyptus* wood cellulose does not, however, correlate significantly with WUE_{sl} suggesting that stable carbon isotope ratios are not useful in determining WUE_{sl} of *Eucalyptus* species. Rather, $\delta^{13}C$ values of *Eucalyptus* are directly related to plant biomass and amount of water consumed in that more negative $\delta^{13}C$ values may be related to high plant biomass and high water consumption. Plant yield is highest when WUE_{sl} is low. Therefore, plant yield for *Eucalyptus* is directly related to the amount of water available. This relationship should be expected, since selection strategies would favour high yield with ample resources.

CHAPTER EIGHT

STABLE CARBON ISOTOPE RATIOS IN CHARCOAL AND WOOD CELLULOSE OF *COMBRETUM APICULATUM* AND *PROTEA ROUPELLIAE* AND RELATIONSHIPS WITH RAINFALL

Introduction

A number of researchers have suggested that the isotopic composition of carbon stored in the growth rings of trees are representative of both $^{13}C/^{12}C$ variations in atmospheric CO_2 as well as physiological responses to environmental change. Previous sections of this report have dealt with this relationship for *Widdringtonia cedarbergensis* from the Cedarberg Mountains near Cape Town. The results of this research has indicated that for *Widdringtonia* the $^{13}C/^{12}C$ record does not correlate significantly with rainfall. Subsequent research using *Eucalyptus* sp. has indicated that for *Eucalyptus grandis* and the hybrid *Eucalyptus grandis x nitens* $^{13}C/^{12}C$ values are indeed significantly related to the amount of water available to the trees (Chap. 6). These results suggest that there is some justification in pursuing the use of stable carbon isotope values of wood cellulose as a rainfall indicator, as was hypothesised at the start of this project provided that the trees chosen for analysis are sensitive to changes in rainfall and that atmospheric isotope correlations are understood (see Chapter 4 and 5).

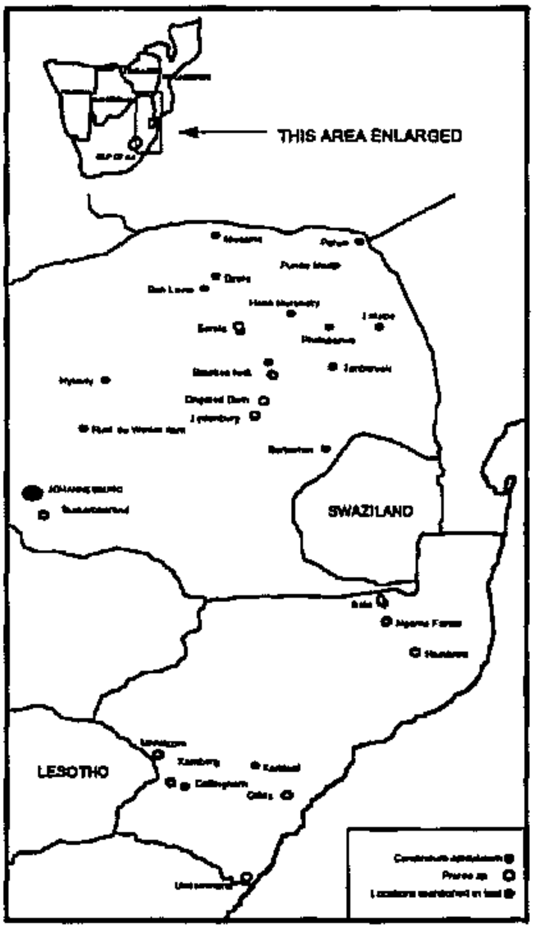

Figure 13. Map showing location of archaeological sites and location from which an extant sample of *P. roupelliae* and *C. apiculatum* were collected.

The principal goal of this section of the project is to demonstrate the potential for using $^{13}C/^{12}C$ ratios of *Combretum apiculatum* and *Protea roupelliae* charcoal from archaeological sites as a climate indicator. An important aspect of the proposed research is to determine and thus exclude any fractionation of the carbon isotope during pyrolosis. To this end, comparisons are made between wood and charcoal to ascertain whether charcoalification causes any fractionation or merely freezes the isotopic ratios of living plants.

Methods

Protea roupelliae is the most common woody species identified in the archaeological record at Mhlwazini Cave and Collingham Shelter in the Drakensberg region of South Africa (Figure 13) while, *Combretum* was identified as the most common woody species in the archaeological site of Dzata from the Soutpansberg Mountains (Figure 13, Chap. 2, February 1992). Samples of these two trees were collected along a rainfall gradient from the summer rainfall region of South Africa (Figure 13).

In dendroclimatology, sample sizes are commonly several tens of trees at each site, with two cores per tree. The time and expense of carbon isotope analysis precludes such density of sampling. Leavitt and Long (1984), in a study designed to determine the sampling strategy and sample size for stable carbon isotope analysis of tree rings, determined that the range in $\delta^{13}C$ values of cellulose around the circumference of a tree is ~1-1.5‰ whereas among individuals it is ~2-3‰. They also determined that pooling the results of analysis from four trees accurately represents site $\delta^{13}C$ values. All results reported in the present study are the means of four trees per site.

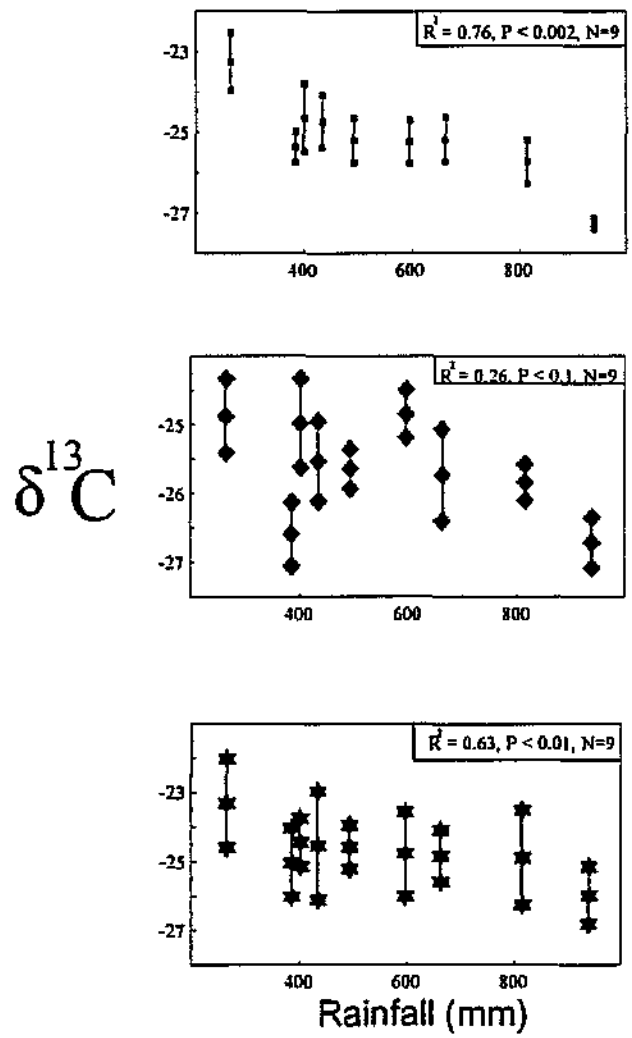

Figure 14. $\delta^{13}C$ ratios for whole wood, wood charcoaled at 400°C, and the cellulose extract of *Combretum apiculatum* along a rainfall gradient in the summer rainfall region of South Africa.

To relate $\delta^{13}C$ values of wood to climate, samples were collected along a rainfall gradient from undisturbed sites as close to rainfall stations as possible. Roads buildings and other constructions were avoided as increased runoff as well as the watering of domestic plants affects $\delta^{13}C$ values. So as to fulfil these requirements most of the samples were collected in private nature reserves or reserves administered by the various Provincial Administrations. These reserves are less disturbed by development and generally have good rainfall records. For the purposes of this study rainfall records were averaged over four years to December 1990 when the samples were collected.

To simulate the natural environment as closely as possible, the samples were air dried for 8 months before charring. In the laboratory a 2 - 3 cm thick disc was cut off the end of each piece of wood before being completely enclosed in tinfoil. These parcels were then placed in a muffle furnace, the temperature of which was gradually taken up to 400° C after one hour. The furnace was then switched off and allowed to cool down slowly. A smaller sample was also charcoaled in the same manner at 500° C.

Without further preparation both whole fresh wood and the charcoaled samples were analysed for $^{13}C/^{12}C$ ratios as described in Chapter 4. Wood cellulose was prepared by milling, soxhlet extraction and cellulose isolation by delignification as described in Chapter four (Green, 1963; Leavitt and Danzer, 1993). All stable carbon isotope analysis was done in the Archaeometry laboratory at the University of Cape Town and stable carbon isotope measures were done on a Micromass 602E spectrometer. References were done against a laboratory gas related to the Chicago PDB marine limestone standard by calibration against six NBS reference standards (see van der Merwe, 1982 and Sealy, 1986).

Results.

The results are not consistent for the two species (Table 7 & 8, Figure 14). For *Combretum apiculatum* there is a significant correlation between $\delta^{13}C$ values of the whole wood sample and rainfall ($R^2 = 0.76$, $P < 0.002$, $N = 9$, Figure 14). This relationship is also true of the cellulose extract ($R^2 = 0.63$, $P < 0.01$, $N = 9$, Figure 14). After charring at 400°C, however, the $\delta^{13}C$ values of the same wood sample are no longer significantly related to rainfall (Table 7, Figure 14).

Mean values for cellulose are -24.16‰ with a standard deviation of 1‰. Averages for whole wood are more negative by 1‰ at -25.2‰ (std. dev. 1‰) while wood charcoaled at 400°C is again more negative by 0.5‰.

Locality	Museum Number	Rainfall (mm)	Wood $\delta^{13}C$,‰	400°C $\delta^{13}C$,‰	500°C $\delta^{13}C$,‰	Cellulose $\delta^{13}C$,‰
Messina	2060	265	-23.78	-24.78	-24.46	-24.56
	2061	265	-24.08	-25.62	-26.45	-23.03
	2062	265	-22.41	-24.97	-23.70	-21.91
	2063	265	-22.71	-24.11	-25.23	-21.50
Letaba	1980	385	-25.50	-26.86	-27.91	-25.28
	1981	385	-25.62	-26.76	-25.45	-24.35
	1982	385	-24.71	-25.80	-25.32	-23.22
	1983	385	-25.61	-26.92	-26.42	-25.08
Blydde River	1940	401	-24.75	-25.72	-26.23	-24.51
	1941	401	-23.56	-24.21	-26.57	-23.94
	1942	401	-25.60	-25.50	-24.85	-23.70
	1943	401		-24.48		-23.39
Pafuri	2050	434	-25.64	-25.79	-26.14	-23.21
	2051	434		-24.61	-26.38	-24.02
	2052	434	-24.14	-26.19	-26.17	-24.33
	2053	434	-24.39	-25.53	-22.47	-24.40
Punda Maria	2040	493	-25.30	-25.86	-26.88	-24.37
	2041	493		-25.76	-28.39	-24.10
	2042	493	-24.48	-25.15	-25.09	-23.43
	2043	493	-25.82	-25.80	-25.06	-24.18
Rust de Winter	2077	597	-26.02	-25.23		-24.71
	2078	597	-24.70	-24.76		-22.86
	2079	597	-25.42	-24.31		-23.89
	2080	597	-24.77	-25.04		-25.43
Nylsvly	1539	663	-25.50	-25.87		-24.95
	1541	663	-25.90	-26.53		-24.50
	1543	663	-24.79	-24.66		-23.53
	1545	663	-24.51	-25.86		-24.13
Barberton	1910	815	-25.82	-26.04		-24.67
	1911	815	-24.86	-25.44		-24.40
	1912	815	-25.90	-26.07		-23.66
	1913	815	-26.36	-25.80		-24.59
Itala	2262	940	-27.47	-27.10	-28.06	-26.56
	2263	940	-27.29	-26.92	-27.55	-25.69
	2264	940	-27.12	-26.72		-25.13
	2265	940	-27.17	-26.13		-24.34

Table 7. Stable carbon isotope ratios for whole wood and charcoaled samples of *Combretum apiculatum* along a precipitation gradient in the summer rainfall region of South Africa.

Previous research has indicated that there is a significant correlation between xylem vessel size and frequency of *P. roupelliae* and rainfall (February, 1992). The results of a stable carbon isotope analysis of a charcoaled fraction of this same sample shows no significant correlation between $\delta^{13}C$ values and rainfall (Table 8). The cellulose extract of a smaller

Location	Museum number	Rainfall (mm)	Charcoal $\delta^{13}C$, ‰	Cellulose $\delta^{13}C$, ‰
Suikerbosrand	2110	765	-26.03	-24.24
	2111	765	-25.43	-24.46
	2112	765	-25.59	-24.89
	2113	765	-27.30	-25.81
Origstad dam	1920	841	-26.46	-24.23
	1921	841	-26.26	-25.12
	1922	841	-26.83	-25.08
	1923	841	-27.29	-25.94
Mhlwazini	2163	868	-24.92	
	2164	868	-25.97	
	2165	868	-24.90	
	2166	868	-26.94	
Itala	2252	942	-26.72	
	2253	942	-26.01	
	2254	942	-25.70	
	2255	942	-26.11	
Sterkspruit	1930	1005	-26.26	-24.72
	1931	1005	-25.35	
	1932	1005	-25.54	-23.85
	1933	1005	-26.15	-25.72
Kamberg	2200	1105	-25.21	-23.84
	2201	1105	-25.15	-23.79
	2202	1105		-23.49
	2203	1105	-24.47	
Mikes Pass	2193	1153	-24.37	
	2194	1153	-24.27	
	2195	1153	-25.99	
	2196	1153	-24.10	
Gillits	2292	1368	-27.76	
	2293	1368	-27.95	
	2294	1368	-27.08	
	2295	1368	-26.98	
Ngome Forest	2272	1410	-26.72	-25.48
	2273	1410	-26.12	-25.11
	2274	1410		-26.62
	2275	1410	-25.96	-25.47
Bourkes Luck	1951	1411	-25.41	-23.89
	1952	1411	-24.70	-24.06
	1953	1411	-25.80	-24.52
	1954	1411	-25.86	-24.49
Serala	2010	1600	-26.61	
	2011	1600	-25.57	
	2012	1600	-26.24	
	2013	1600	-25.03	
Umtamvuna	2313	1664	-25.37	
	2314	1664	-26.03	
	2315	1664	-24.05	
	2316	1664		

Table 8. Stable carbon isotope ratios for whole wood and charcoaled samples of *Protea roupelliae* along a precipitation gradient in the summer rainfall region of South Africa.

sample was re-analysed. Again, there is no significant correlation between $\delta^{13}C$ values and rainfall (Table 8). Mean values for cellulose are -24.76‰ whereas the charcoal sample has a mean of -25.88. This represents a fractionation effect of ~1‰ from cellulose to charcoal.

Discussion

A stable carbon isotope analysis of *Combretum apiculatum* whole wood and cellulose exhibits very different results to that of *Protea roupelliae* in that rainfall is indeed significantly related to $\delta^{13}C$ values. The difference in results for the two species can probably be attributed to *C. apiculatum* being drought deciduous, with very definite seasonality of growth related to rainfall. *Protea roupelliae* on the other hand, does not lose its leaves, rather, these leaves may stay on the plant for a number of years (pers obs). This tendency could affect the isotope ratios in that $\delta^{13}C$ values of previous years are retained in the leaf and may be distributed to the rest of the plant in subsequent years. Unlike *C. apiculatum*, *P. roupelliae* grows in a wide variety of habitats and on a range of soil types as well as in areas of very high rainfall. As a result, a range of ecophysiological factors and environmental variables may account for the variations in $\delta^{13}C$ values among trees from different locations found in this study. The non significant results obtained here for *Protea roupelliae* suggest that this species cannot be used in climate reconstructions.

The highly significant correlations of $\delta^{13}C$ values and rainfall for *C. apiculatum* are, however, not manifested in the sample charred at 400° C. Prior and Gasson (1993) demonstrate that at 400° C the percentage weight loss of *Combretum zeyheri* was approximately 47%. The cell walls of wood are composed of a characteristic mixture of polymers of cellulose, carbohydrates and lignin Panshin and de Zeeuw, (1977). Cellulose and holocellulose have become the preferred material for isotopic analysis of tree rings because of the singular composition of cellulose relative to whole wood tissue which has many compounds of different isotopic composition (Leavitt and Danzer, 1993). Prior and Gasson (1993) suggest that during pyrolosis hemicelluloses degrade at temperatures between 200 and 300°C followed by cellulose above 240° C and lignin above 280°C. Thus the main components of wood are degraded at temperatures under 300°C. On average this degradation is represented in $\delta^{13}C$ values becoming more negative by 0.5 ‰ at temperatures of 400°C and by 1‰ at temperatures of 500° C. However, this fractionation is not a constant with different pieces of wood reacting differently depending on a number of factors including size and location to the heat source. As a result, the significant correlations obtained for both whole wood and cellulose extract of *Combretum apiculatum* is not maintained after charcoalification.

Conclusion

The results of a stable carbon isotope analysis of *Combretum apiculatum* across a rainfall gradient indicate that $\delta^{13}C$ values of wood cellulose can be a useful rainfall indicator. However, not all woody species exhibit the same traits. $\delta^{13}C$ values of *P. roupelliae* are not related to rainfall because this species grows in high rainfall areas, over a diversity of habitats. This suggests that, for rainfall and carbon isotope ratios to be correlated, water has to be one of the major limitations to growth. Fractionation of the carbon isotope does occur when wood is charcoaled. The amount of fractionation is constant depending on the temperature at which the charcoal is formed. As the temperature of an open fire is not consistent and because the charcoal recovered from archaeological sites is formed in open fires it is not possible to correct isotope values for any given temperature. Therefore, climate reconstruction based on $\delta^{13}C$ values of wood charcoal from archaeological sites is not possible.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

Introduction

This report discusses the procedures necessary for an assessment of a new method for climate reconstruction using wood charcoal excavated from archaeological deposits. A result of this work has been the first tree ring chronologies for South African indigenous woody species since that generated by Dunwiddie and La Marche (1980) as well as a better understanding of the relationship between $\delta^{13}C$ values of wood cellulose and rainfall. A combination of these results has contributed significantly toward the ultimate goal of a high resolution (annual) reconstruction of the rainfall history of the last 300 years for South Africa.

The primary objectives of the project are set out on page 3 of this report. These objectives were based on previous research which has indicated that $^{13}C/^{12}C$ ratios are good indicators of water available to plants (Freyer and Belacy, 1983; Leavitt and Long, 1986). The important consideration here is that with increased water stress stomatal closure results in reduced CO_2 uptake resulting in more positive stable carbon isotope values. The present study is a systematic analysis of this relationship, in six developmental steps, the main aim of which was to determine whether or not stable carbon isotope ratios of charcoal recovered from well dated archaeological sites could be useful in providing reliable proxy rainfall data beyond the reach of the historic record.

To achieve the objectives the main species of wood represented in the archaeological deposits from Mhlwazini Cave and Collingham Shelter were identified. However, prior to isotopic analysis of a modern sample of this species the dendrochronological potential of two *Podocarpus* species and a *Widdringtonia* were assessed. The results of this analysis indicate that with a 25% margin of error, age determination of *Podocarpus* sp. is possible. Ring width indices do not however correlate significantly with rainfall variables. Furthermore, a combination of poorly defined, locally absent and converging rings make cross-dating between different trees from the same locality an impossible task. For too long now dendrochronological research in South Africa has focused on the various *Podocarpus* species. The research and conclusions outlined in the present study, however has indicated that such a focus is unwarranted. In 1980, Dunwiddie and La Marche, demonstrated the dendrochronological potential of *Widdringtonia cedarbergensis*. This section of the project confirms their original hypothesis that unlike the various *Podocarpus* species *Widdringtonia cedarbergensis* forms a new ring on an annual basis that is identifiable in cross section as a separate individual ring. The very clear annual rings formed by *Widdringtonia cedarbergensis* make this species ideal for an assessment of the relationship between $\delta^{13}C$ values of wood cellulose and annual rainfall. On analysis, however, the $\delta^{13}C$ record from the pooled trees at the De Bos site in the Cedarberg Mountains near Cape Town do not correlate significantly with the rainfall record. What this $\delta^{13}C$ record does show is a strong correlation between stable carbon isotope ratios of tree rings and atmospheric CO_2 levels. This correlation is manifested by less negative $\delta^{13}C$ values from 1900 to 1947 and a clear decrease from then to 1977 which is very similar to the data obtained by other researchers (Freyer and Belacy, 1983; Friedli, *et al.*, 1986; Leavitt and Lara, 1994). The present study presents only the second $\delta^{13}C$ chronology from the southern hemisphere, and the first with annual resolution, to show a decline in $\delta^{13}C$ ratios over time.

Rather than trace the anthropogenic contribution to atmospheric CO_2 levels the principal goal of this project is to assess the potential for using stable carbon isotope ratios of charcoal as a rainfall indicator. To meet this objective an understanding of the relationship between rainfall and stable carbon isotope ratios of wood cellulose is necessary. If $\delta^{13}C$ values of *Widdringtonia cedarbergensis* do not relate significantly to rainfall then the very premise on which this project has been based is not correct. That is, that with increased water stress, stomatal closure results in reduced CO_2 uptake and therefore more positive $\delta^{13}C$ values which are retained in the wood of the tree. So as to gain a better understanding of the relationship between $\delta^{13}C$ values, wood cellulose and water consumption of trees, samples of *Eucalyptus* which had been experimentally grown under controlled conditions were obtained from the CSIR division FORESTEK. The results of this section of the project indicate that for *Eucalyptus grandis* and the hybrid *Eucalyptus grandis x nitens* carbon isotope ratios become more negative in the wetter treatment as well as with increased water consumption. These results indicate that there is some justification for pursuing the use of $\delta^{13}C$ values of wood cellulose in rainfall reconstructions provided that the trees chosen for analysis are sensitive to changes in rainfall and that atmospheric isotope correlations are understood.

An earlier project (February 1992) had identified *Combretum apiculatum* as the most common woody species in the archaeological deposits from Dzata in the Northern Province while this project has identified *P. roupelliae* as the most common species from two archaeological sites in the Drakensberg. A $\delta^{13}C$ analysis of the cellulose content of the wood of a number of samples of *Combretum apiculatum* across a rainfall gradient indicates that $\delta^{13}C$ values of wood cellulose can be significantly correlated with rainfall. The results of an isotopic analysis of a *Protea roupelliae* sample suggest that not all woody species exhibit the same traits as there is no significant correlation between isotope values and rainfall. Furthermore, there is a consistent fractionation of the carbon isotope with increased temperature. Charcoal from an open fire is not formed at a constant temperature because of the temperature differences between such fires as well as within the same fire. These inconsistencies make it very difficult to correct the isotope values of the charcoal sample for the temperature at which it was formed even though there is a consistent relationship between the temperature at which the charcoal was formed and the degree of fractionation. This fractionation affect means that the primary objective of this study, rainfall reconstructions based on $\delta^{13}C$ values of wood charcoal from archaeological sites, is not viable. Following on this conclusion secondary objectives c, d and e as set out on page 3 of this report cannot be met because there is no basis for continuing to pursue such research.

Concluding remarks.

While the final conclusion is a negative one, there are a number of positive results which have emanated from this study. The charcoal identification and relative abundance described in Chapter Two is a simple method for determining environmental change which does give information for palaeoclimatic interpretation that is independent of and will clarify data obtained by other independent methods such as xylem analysis (February, 1992).

The assessment of the dendrochronological potential of two *Podocarpus* species in Chapter Four should finally lay to rest the use of this species in dendrochronological research in South Africa. While the establishment of two further chronologies to add to the one already established by Dunwiddie and La Marche (1980) makes a real contribution to the development of dendrochronology in South Africa. The research potential of this species is extremely important for any further research attempts to develop a high resolution rainfall record for South Africa. More dendrochronological research using this species is a definite priority not only for developing a ring width index chronology related to rainfall but also for an assessment of the anthropogenic impact on atmospheric CO_2.

The results of the stable carbon isotope analysis of *Eucalyptus* species suggests a strong relationship between $\delta^{13}C$ values and water use. These findings are not only useful for verifying the relationship between isotope values and water use but may be useful in cloning programmes where the main purpose is to identify drought tolerant and productive species that will ensure forest production in low rainfall areas.

The final result is also important for similar research projects working with $\delta^{13}C$ values and either archaeological or soil samples in that all charcoal would have to be removed from such samples prior to analysis because of the unknown fractionation factor.

Archiving of data

All the data as well as the slide, wood, charcoal and cellulose collections generated by this project will be appropriately stored for future retrieval at the South African Museum in Cape Town.

PUBLICATIONS

There have been a number of publications resulting from this study. The following is a list of these publications.

Scientific:

1995: February E.C. (1995) Archaeological charcoal as a potential tool for environmental management. *Veld and Flora*. **81** (1): 10-11.

February E.C., Stock, W.D., Bond, W.J. and Le Roux, D.J. Relationships between water availability and selected xylem vessel characteristics in *Eucalyptus grandis* and two hybrids. *IAWA Journal*. 16 (3): 269 276.

1994: February E.C. (1994) Rainfall reconstruction using wood charcoal from two archaeological sites in South Africa. *Quaternary Research*. **42**:100-107.

February E.C. (1994) Palaeoenvironmental reconstruction using wood charcoal as a conservation management tool. *South African Journal of Science*. **90**:549-551.

1993: February E.C. (1993) Sensitivity of Xylem vessel size and frequency to rainfall and temperature: implications for palaeontology. *Palaeontologia Africana*., **30**, 91-95.

1992: February E.C. (1992) Archaeological charcoals as indicators of vegetation change and human fuel choice in the Late Holocene at Elands Bay, western Cape Province, South Africa. *Journal of Archaeological Science* **19**:347-354.

February E.C. and van der Merwe N.J. (1992) Stable carbon isotope ratios of wood charcoal during the past 4000 years: anthropogenic and climatic influences. *South African Journal of Science*. **88**:291-292.

Popular:

1994 February E.C. (1994) Applied Archaeology? Potential contributions to environmental management. *The Digging Stick* **11**,2:8. ISSN 1013-7521

Prins H., Scholtz B. & February E.C. (1994) *Future directions for heritage conservation in South Africa*. Assessors report arising from a series of six regional work sessions organised by the National Monuments Council.

1993: February E.C. (1993) More to wood than meets the eye. *Muse news*. Monthly newsletter and calendar of events S.A. Museum Cape Town.

February E.C. (1993) Palaeoenvironmental reconstruction using wood charcoal: conservation management in the Drakensberg. *Protea Atlas Newsletter* **19**:11. ISSN 1018-337X.

February E.C. (1993) A visit to archaeological sites in the northern Cape. *The Digging Stick* **10**,2:11-12. ISSN 101-7521.

February E.C. & Joubert H. (1993) Researchers use wood anatomy to reconstruct SA rainfall history. *SA Waterbulletin* 19,3:14-17. ISSN 0258-2244.

February E.C. (1993) SASQUA 1993 Post Conference Excursion. *Sasqua Newsletter* **24**:4-6.

In Press:

In Press — February E.C. "Coffins", wood and the status of the people buried. *Journal of Archaeological Science*.

CONFERENCES ATTENDED AND SCIENTIFIC LECTURES GIVEN

1995: Presented a paper at the IGBP Miombo Meeting held at Zomba Plateau Malawi.

Presented a paper at the Regional Conference of the International Geosphere-Biosphere programme.

Presented a paper at the XII biennial conference of the Southern African Society for Quaternary Research.

Attended a Scientific Workshop under the auspices of the Fynbos Forum.

Presented a seminar at The Tree Ring Laboratory, the University of Arizona.

1994: Presented two papers at the Biennial conference of the Southern African Association of Archaeologists.

1993: Presented a paper at the 9th Annual conference of the South African Association of Botanists.

Presented a paper at the 11th Biennial conference of the Southern African Society for Quaternary Research.

Presented a seminar at The Tree Ring Laboratory, the University of Arizona.

Gave a presentation to the Water research Commissioners at the University of Cape Town.

1992: Presented a paper at the Biennial conference of the Southern African Association of Archaeologists.

Presented a paper at the Biennial conference of the Palaeontological Society of South Africa.

Presented a seminar at The National Museum Bloemfontein.

POPULAR AND EDUCATIONAL LECTURES

1993: Gave a lecture to the Friends of the South African Museum.

Gave a Public lecture at the South African Museum.

Interviewed on the Radio Programme "Calling all farmers".

1992: Invited to lecture at the Annual meeting of the Water Institute of South Africa.

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