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Growth trends and water use efficiency of Pinus Pinaster Ait. in response to historical climate and groundwater trends on the Gnangara Mound, Western Australia

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GROWTH TRENDS AND WATER USE EFFICIENCY OF *PINUS PINASTER* AIT. IN RESPONSE TO HISTORICAL CLIMATE AND GROUNDWATER TRENDS ON THE GNANGARA MOUND, WESTERN AUSTRALIA

By

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ABSTRACT

In Western Australia, groundwater accounts for about 57% of Perth's water supply. The majority of this is from the Gnangara Mound, the largest superficial aquifer on the Swan Coastal Plain. Prior to the mid 1970's groundwater of the superficial aquifer reached a semi-steady state, however since this period levels have been steadily falling. This decline coincides with a dramatic change in Perth's climate, groundwater abstraction and maturation of pine plantations.

The influence of pine plantations upon groundwater recharge is well understood, however there is paucity of information about groundwater use, in particular whether pines directly access shallow groundwater resources. This study used traditional dendrochronology techniques to evaluate the influence of historical climate and groundwater trends upon growth trends of *Pinus pinaster* Ait stands on the Gnangara Mound, Western Australia. Twenty eight (28) trees were destructively sampled, 16 from the Gnangara plantation and 12 from the Pinjar plantation. Three age classes, being young (<15 years), intermediate (15-25 years) and old (>25 years) and two depth to groundwater regimes were selected to meet the study's objectives. The Gnangara plantation sites were selected to represent *Pinus pinaster* Ait. plantations which potentially have access to groundwater resources (<5 mbgl), and the Pinjar plantation sites represented those without (>20 mbgl).

From each tree a whole-tree cross-section was removed and tree growth-rings were delineated to assess annual growth trends. Standard dendrochronology techniques were used to developed tree growth-ring chronologies. These chronologies were then used to evaluate the influence of historical climate and depth to groundwater trends, and historical silvicultural treatments upon growth trends.

The key findings of the tree growth-ring analysis are that growth trends of *Pinus pinaster* Ait. occurring on the Gnangara Mound, are significantly influenced by silvicultural treatments and cumulative growing season rainfall, irrespective of the underlying groundwater trends. Thinning in particular significantly influenced ring

growth. The growth increment of trees sampled from the Pinjar and Gnangara plantation sites were all responsive to rainfall trends however the trees located in the Pinjar plantations were slightly more responsive. Therefore growth trends did not indicate whether those trees underlain by a shallow groundwater resource (<5 mbgl) directly access this resource. The differential responses to rainfall were most likely attributed to site specific soil properties. There was no significant correlation identified between tree growth-ring trends and the other tested variables of minimum, maximum and cumulative temperature, evaporation and depth to groundwater trends.

Water use efficiency was assessed by analysing $\delta^{13}C$ signatures of whole-wood from annual tree growth-rings and from foliar material collected from the trees destructively sampled for chronology development. Analysis of foliage material revealed that needle $\delta^{13}C$ values are significantly influenced by canopy position and branch length characteristics and are therefore considered unsuitable for the evaluation of the influence of historical climate and groundwater trends. Nitrogen concentrations analysed from foliar material was used as a proxy for soil nutrients. Results indicated the soil nutrient conditions at the Gnangara and Pinjar plantation study sites were similar, therefore unlikely to account for differences between $\delta^{13}C$ values. It is however recommended that future assessment of $\delta^{13}C$ assess soil nutrients including nitrogen and phosphorus.

Results from analysis of $\delta^{13}C$ in tree growth-rings revealed that there were no consistent correlations between $\delta^{13}C$ and historical climate and groundwater trends. Therefore $\delta^{13}C$ is not a suitable indicator of intrinsic water use efficiency. The $\delta^{13}C$ trends however did enhance the interpretation of growth responses to historical climate and groundwater trends and silvicultural treatments.

From the results obtained from this study, it was concluded that *Pinus pinaster* Ait. is a suitable species for chronology development and data derived from the application of dendrochronology techniques may enhance the development of future forest management programs.

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Lastly, I hope that education remains accessible to all Australians and that the broader community continues to support academic endeavour and the pursuit of environmental research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Groundwater has in recent times become an important source of fresh water, chiefly in countries with dry or arid climates (Bouwer, 1989). Australia is no exception and its dependence upon groundwater has increased significantly due to escalating demands that can not be met by surface water reservoirs (Government of Western Australia, 2003). Although a renewable resource, the quantity and quality of groundwater resources is finite. Abstraction of groundwater at rates greater than replenishment can result in depletion of groundwater resources (Davidson, 1995). Unsustainable groundwater abstraction may also have environmental consequences, particularly in regions with groundwater dependant ecosystems (Aplin, 1976; Groom, Froend, & Mattiske, 2000; Murray, Zeppel, Hose, & Eamus, 2003).

Groundwater use may be regarded as an acceptable short-term solution to water shortages however the long-term sustainability of groundwater resources requires an understanding of the hydraulic properties of the aquifer and those factors influencing recharge and discharge (Williamson & Lawrence, 1980). Water resource managers therefore must account for all users of groundwater before determining sustainable yields, failure to do so may result in environmental, economic and societal costs (Salama, Bekele, Hatton, Pollock, & Lee-Steere, 2002).

1.1.1 The Gnangara Mound

In Western Australia, groundwater accounts for about 57% of Perth's water supply (Water Corporation, 2004). The majority of this is abstracted from the Gnangara Mound (Western Australian Planning Commission, 2001). The Gnangara Mound is the largest superficial aquifer on the Swan Coastal Plain, covering an area of 2,200 km^2, and bounded by Gingin Brook and Moore River in the North, Ellen Brook in the east, the Swan River in the south, and the Indian Ocean in the West (Farrington, Greenwood, Bartle, Beresford, & Watson, 1989; Sharma & Craig, 1989) (Figure 1-1).

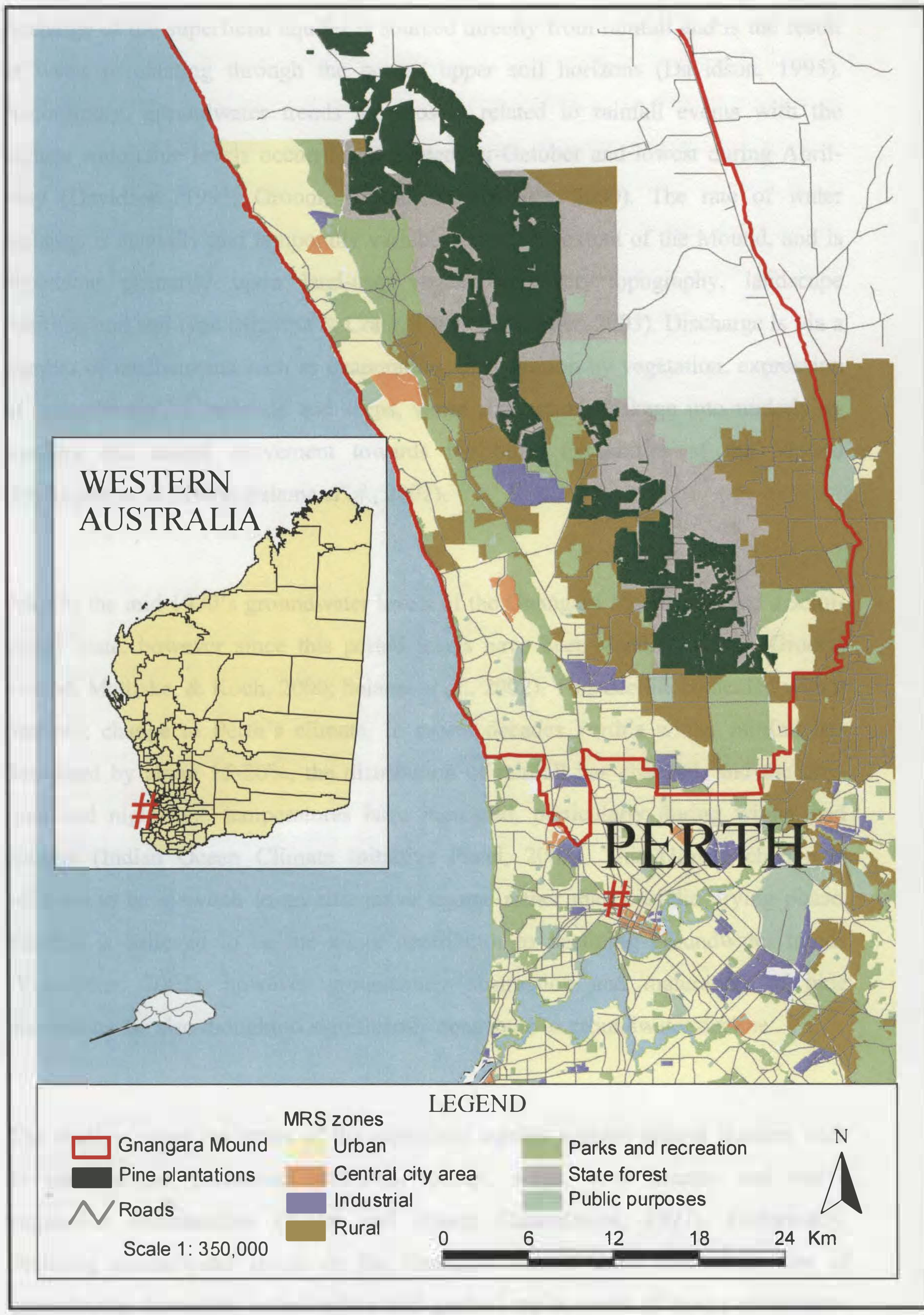

Figure 1-1: Overview of the Gnangara Mound and the various land uses throughout the Perth Metropolitan Region Scheme (map produced by the author).

Recharge of the superficial aquifer is sourced directly from rainfall and is the result of water percolating through the porous upper soil horizons (Davidson, 1995). Accordingly, groundwater trends are closely related to rainfall events with the highest watertable levels occurring in September-October and lowest during April-May (Davidson, 1995; Groom, Froend, & Mattiske, 2000). The rate of water recharge is spatially and temporally variable across the extent of the Mound, and is dependant primarily upon land-use, vegetative cover, topography, landscape position, and soil type (Sharma & Craig, 1989; Yesertener, 2003). Discharge is via a number of mechanisms such as evaporation, transpiration by vegetation, expression of groundwater in wetlands and seeps, water abstraction, leakage into underlying aquifers and lateral movement towards the outer extremities of the Mound (Farrington *et al.*, 1989; Salama *et al.*, 2002).

Prior to the mid 1970's groundwater levels of the Gnangara Mound reached a semi-steady state, however since this period levels have been steadily falling (Groom, Froend, Mattiske, & Koch, 2000; Salama *et al.*, 2002). This decline coincided with a dramatic change to Perth's climate. In recent decades Perth's winter rainfall has decreased by about 15-20%, the distribution of rainfall has changed, and the day-time and night-time temperatures have increased, particularly during winter and autumn (Indian Ocean Climate Initiative Panel, 2002). This climate change is believed to be a switch to an alternative regime rather than a cyclic drying phase. Rainfall is believed to be the major contributor to declining groundwater trends (Yesertener, 2003), however groundwater abstraction and maturation of pine plantations are also thought to significantly contribute to groundwater decline .

The shallow water resources of the superficial aquifer support natural features such as seasonal and permanent wetlands, springs, seeps, cave streams and native vegetation communities (Water and Rivers Commission, 1997). Historically, declining groundwater levels on the Gnangara Mound have resulted in loss of groundwater dependant communities and gradual replacement of mesic ecosystems with xeric ecosystems (Groom, Froend, & Mattiske, 2000; Groom, Froend, Mattiske *et al.*, 2000; Groom, Froend, Mattiske, & Gurner, 2001).

The demand for groundwater resources for public water supply from the Gnangara Mound has trebled over the last fifteen years and is expected to double over the next twenty years (Welker Environmental Consultancy, 2002). Alternative sources of water are currently being developed such as the seawater desalination plant in Kwinana and the development of new groundwater and surface water sources (Water Corporation, 2004). However given the continued demand for public water supply, and the likelihood that the recent climate trends will continue, research has been initiated to facilitate sustainable management of the superficial aquifer.

1.1.2 The dependence of *Pinus pinaster* Ait. plantations on shallow groundwater resources

Pine plantations were established throughout the Gnangara Mound to meet the States demands for quality sawlogs (Butcher, 1979). Pine plantations, which are comprised predominantly of *Pinus pinaster* and to a lesser degree *Pinus radiata*, currently cover an area of about 22,000 hectares, which is about 10% of the Gnangara Mounds area. The replacement of native vegetation communities with pine plantations is thought to have contributed to the decline of groundwater levels of the superficial aquifer by increasing interception of rainfall, and enhanced transpiration and evaporation rates (Butcher, 1977; Farrington & Bartle, 1991; Salama *et al.*, 2002). The influence of pine plantations upon groundwater recharge is relatively well understood, however there is paucity of information about pine groundwater use, particularly the influence of shallow groundwater tables upon growth.

Approximately 50% of the root volume in *Pinus pinaster* Ait. can occur within the upper 10cm (Danjon, Bert, Godin, & Trichet, 1999). This portion of the root structure is largely responsible for accumulation of soil moisture and nutrients, whilst the dominant taproot plays an important role in accessing soil moisture at depth. Uptake of water by pines is primarily through the root structure, and is driven by gradients in water potential (Peterson, Enstone, & Taylor, 1999). As the soil dries, the water potential decreases until a point is reached where soil moisture can no longer be physically extracted (Butcher, 1977). As water deficits increase, signals from the root structure are transferred throughout the plant to reduce water loss. In

particular, water conservation through stomatal closure as a consequence of root ABA production (Dubos & Plomion, 2003). Drying of the surface soils may induce stomatal closure even though water resources may be available at depth (Teskey & Sheriff, 1996).

Historically, stands of mature pine on the Gnangara Mound were believed to access water resources within the top 6m of the soil profile, therefore pines underlain by shallow aquifers (<6 m) were thought to directly access these groundwater resources (Havel, 1968; Butcher, 1979). Assuming that the root system maintains contact with the water table throughout the year then interannual growth trends would be relatively consistent over time regardless of rainfall trends (i.e. similar growth between years). The implications of the this theory are that stands of mature pines in contact with the groundwater table would not only reduce recharge of rainfall, but also contribute to the discharge of groundwater resources through transpiration. This would significantly influence the management of pine plantations in lieu of the trend of declining groundwater levels of the superficial aquifer of the Gnangara Mound.

1.2 SIGNIFICANCE AND AIMS OF THIS STUDY

Pine plantations cover approximately 10% of the Gnangara Mound, a region which is valued for water production, timber production and environmental conservation (CALM, 1999). The sustainable management of water resources of the Gnangara Mound in particular requires a better understanding of the plant/water relations of pine plantations. This is important given the anticipated increased demand upon groundwater resources in the future, particularly if the decline in annual rainfall experienced since the 1970's continues.

The objectives of this study were to evaluate the influence of historical climate and groundwater regimes upon the growth trends and intrinsic water use efficiency of *Pinus pinaster* Ait. stands occurring on the Gnangara Mound, Western Australia. Specific objectives are as follows:

i. Evaluate historical growth trends of Pinus pinaster Ait. stands occurring on two divergent groundwater regimes (<5 m and >25 m to groundwater), to address the hypothesis that pine plantations on the Gnangara Mound do not directly access groundwater resources, but instead rely upon rainfall and soil moisture.

ii. Evaluate the applicability of the stable carbon isotope composition ($\delta^{13}C$) stored in plant and leaf material as an index of historical water availability, to enhance the understanding of water use efficiency of Pinus pinaster Ait stands occurring on two divergent groundwater regimes (<5 m and >25 m to groundwater) on the Gnangara Mound.

1.2.1 Thesis outline

Chapter 2 is the site selection chapter, providing a general description of the climate, geology and hydrology of the study sites. The chapter also outlines a brief history of *Pinus pinaster* Ait. plantations, the establishment practices, and improvements made to the original seed-stock. The remainder of the chapter provides details associated with site selection criteria, methodology, sampling protocols, and an overview of the GIS based desktop study, site visit and drilling program.

Chapter 3 provides an overview of the phenology of *Pinus pinaster* Ait. The site-specific geology, climate and groundwater trends and forest stand attributes are then detailed. The remainder of the chapter reports on the evaluation of growth trends of *Pinus pinaster* Ait. and the influence of historical climate, groundwater trends, and silvicultural treatments.

Chapter 4 integrates the results from Chapter 3 with stable carbon isotope measurements ($\delta^{13}C$) of tree growth-rings and foliar material. $\delta^{13}C$ results are used to evaluate the influence of historical climate, groundwater trends, and silvicultural treatments upon intrinsic water use efficiency.

Chapter 5 is a synthesis of the findings from Chapter 3, and Chapter 4, and comments on: (1) growth trends of *Pinus pinaster* Ait. and the significance of silvicultural treatments and rainfall; (2) the applicability of $\delta^{13}C$ as an indicator of historical water availability.

CHAPTER 2: SITE SELECTION

2.1 SITE DESCRIPTION

The groundwater table on the Gnangara Mound is closely related to surface topography (Dames and Moore, 1986). Consequently two regions on the Gnangara Mound were selected as suitable for the purpose of this study, these being the Gnangara and the Pinjar plantations. The Gnangara plantation was selected to represent stands of *Pinus pinaster* Ait. with access to shallow groundwater resources, <5 metres below ground level (mbgl), and the Pinjar plantation to represent those without (>20 mbgl). The Gnangara plantation study sites are located ~30 km northeast of Perth at the south-eastern extent of the Gnangara Mound (Figure 2-1), and the Pinjar plantation sites are located ~45 km north/northwest of Perth toward the central region of the Gnangara Mound. The distance between the two study sites is approximately 25 km.

The general characteristics of these two regions are described in this Chapter, whilst the site-specific climate, geology, hydrology and stand characteristics are detailed in Chapter 3. The sampling protocols used to identify sites which meet the depth to groundwater, and age-class criteria developed for this study are detailed below.

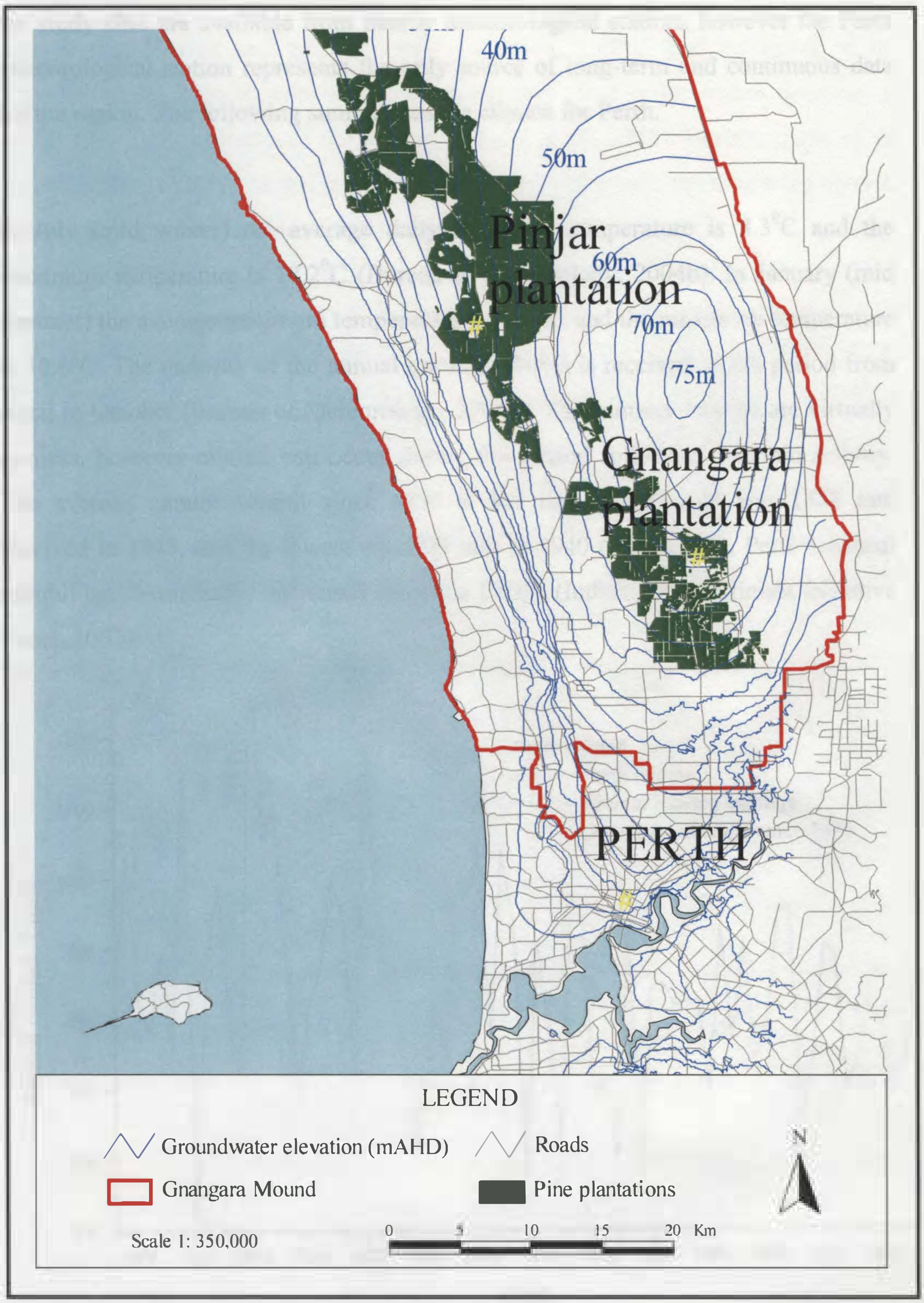

Figure 2-1: Map indicating location of Gnangara and Pinjar plantation study sites on the Gnangara Mound, Western Australia (map produced by the author).

2.1.1 Climate

The climate of the Gnangara Mound is best described as Mediterranean, with cool wet winters and hot dry summers (McArthur & Bettenay, 1960). Climate records for the study sites are available from nearby meteorological stations however the Perth meteorological station represents the only source of long-term and continuous data for the region. The following summarises the climate for Perth.

In July (mid winter) the average daily minimum temperature is 8.3^{0}C and the maximum temperature is 18.2^{0}C (Bureau of Meteorology, 2004b). In January (mid summer) the average minimum temperature is 17.9^{0}C, and the maximum temperature is 30.6^{0}C. The majority of the annual rainfall (~90%) is received in the period from April to October (Bureau of Meteorology, 2004b). The summer months are virtually rainless, however rainfall can occur during this period following cyclonic activity. The average annual rainfall since 1876 is 861 mm, the highest was 1338 mm received in 1945, and the lowest was 509 mm in 1940 (Figure 2-2). Perth's annual rainfall has dramatically decreased since the 1970's (Indian Ocean Climate Initiative Panel, 2002).

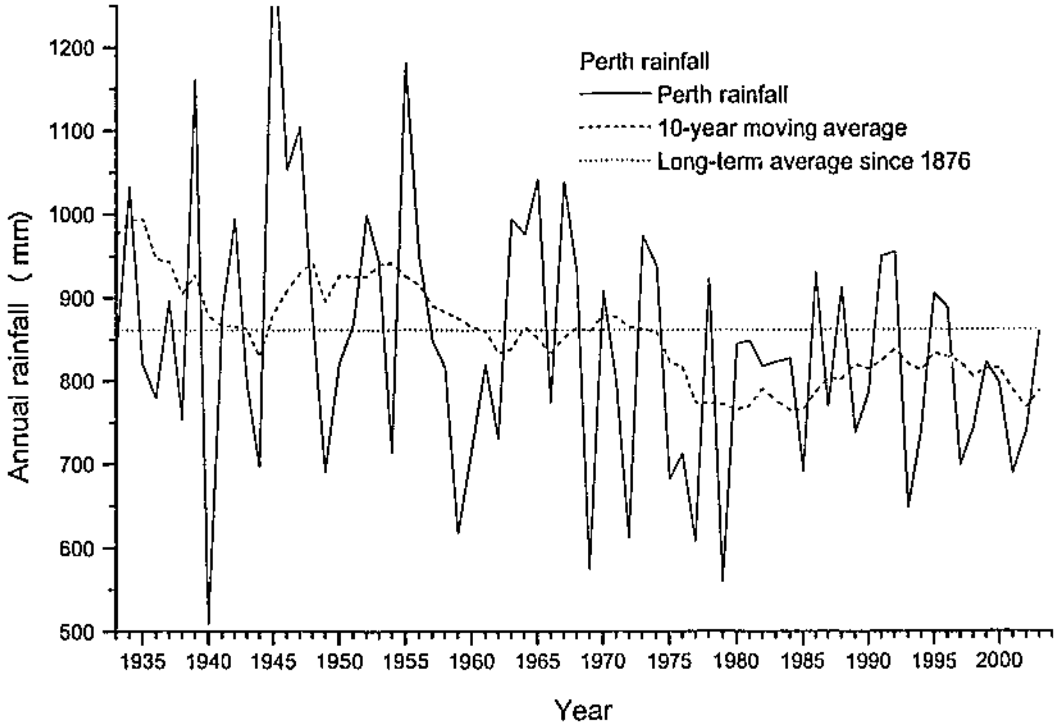

Figure 2-2: Perth's annual rainfall from 1933 to 2003 and the long-term average (861 mm), and the 10 year moving average since 1876 (Bureau of Meteorology, 2004b).

2.1.2 Geomorphology

The geology of the Gnangara Mound is characterised by a complex Quaternary-Tertiary aged superficial formation comprising of sand, silt, and clay in variable proportions (Dames and Moore, 1986; Davidson, 1995). The thickness of the superficial formation is variable from approximately 10 m in the eastern boundary to about 100 m in the centre of the Mound (Salama *et al.*, 2002). Beneath most of the superficial formation Cretaceous aged sedimentary rocks form the confining layer of the shallow aquifer (Davidson, 1995).

The two key geological entities pertaining to the Gnangara and Pinjar plantations are the Bassendean, and Spearwood Dune Complexes respectively. The Bassendean Dune Complex is the oldest of the dune systems and is characterised by nutrient poor, grey quartz sands, which are depauperate of calcium, iron and most other minerals, consequently Bassendean sands are infertile and have poor moisture holding capacity (Seddon, 1972). Sandy wetlands are present in some regions of this complex due to the presence of an almost impermeable ferruginous (coffee rock) hardpan at shallow depths (~1m) (Seddon, 1972; Dames and Moore, 1986). The Spearwood Dune Complex is younger than the Bassendean system and is characterised by brown or yellow sand underlain by a hard capping of precipitated limestone, then a core of aeolianite (McArthur & Bettenay, 1960). The depth of the upper sandy horizons is variable and at some places the limestone capping and aeolianite are exposed at the surface (Seddon, 1972).

2.1.3 Hydrology

Recharge of the superficial aquifer is sourced directly from rainfall and is the result of infiltration of water through the porous upper soil horizons (Davidson, 1995). Accordingly, groundwater trends are closely related to rainfall events with the highest watertable levels occurring in September-October and lowest during April-May (Allen, 1976; Davidson, 1995; Groom, Froend, & Mattiske, 2000). Generally, groundwater levels of the superficial aquifer are declining as a direct result of declining rainfall trends (Indian Ocean Climate Initiative Panel, 2002), increased

abstraction of groundwater resources (Davidson, 1995), and reduced recharge of rainfall beneath high density, mature pine plantations (Farrington & Bartle, 1991).

2.1.4 *Pinus pinaster* Ait. plantations

Pinus pinaster Ait. was initially selected as a plantation species on the Swan Coastal Plain due to their ability to grow on the nutrient poor soils (Butcher, 1979), relative tolerance to drought conditions (Hopkins, 1971), and resilience to low intensity fires (Burrows, Ward, & Robinson, 2000). The first *Pinus pinaster* seeds were sourced from France, Italy and Portugal (Perry, 1940). Seed sourced from the Leiria Forests in Portugal (*Pinus pinaster* Ait.) was quickly recognised as having superior form and growth in the Western Australian conditions. Consequently this genotype became the major seed stock for initial plantations (Stoate, 1939; Perry, 1940; Hopkins, 1971; Perry & Hopkins, 1976).

The general practice for establishment of pine stands on the Gnangara Mound is to grow seedlings in a nursery environment until they are suitable for planting, this is typically for a period of one year (Stoate, 1939). Initial stocking rates are relatively high at about 2000 stems per hectare (s/ha^{-1}), then stands are progressively thinned over a number of years to increase merchantable volume (S. Wood, pers. comm, 22nd March, 2004). This process reduces branch development, a major determinant of knot size in *Pinus pinaster* Ait. sawlogs (Butcher & Hopkins, 1993). Improvements to seed stock were gradually made, particularly in the late 1960's and early 1970's resulting in improved timber quality and yield (Butcher & Hopkins, 1993). Thus lower stand densities attained similar returns with the additional benefit of increased recharge of rainfall to the superficial aquifer beneath less dense stands (Butcher, 1977). Since 1972, all seed used for *Pinus pinaster* Ait. plantations in Western Australia were sourced from genetically improved seed orchards (Butcher & Hopkins, 1993).

Due to the increased demand upon groundwater resources of the superficial aquifer, planting of pines throughout the Gnangara Mound for timber production ceased in

1988. All plantations subsequent to this period were established for orchard seed stock, research purposes, or for the sale of Christmas trees to the general public (S. Wood, pers. comm. March 22, 2004).

2.2 Sampling protocols

2.2.1 Desktop study

In order to achieve the study's objectives, each of the factors potentially influencing tree growth rates and water availability, where practical were isolated. Due to the historical changes to forest management strategies and silvicultural treatments it was not possible to find stands with identical stand properties such as stand density, soil types and basal area.

Consequently six site classification criteria were determined. These were three age classes, being young (<15 years), intermediate (15-25 years), and old (>25 years); and two depth to groundwater characteristics, being shallow (<5 mbgl) and deep (>20 mbgl). The caveats upon site selection were that different age classes within each groundwater regime are to be located close to each other, and with a relatively similar history of silvicultural treatments. Where feasible, this ensured that measured growth and $\delta^{13}C$ differences of stands occurring in each groundwater regime (i.e. Gnangara and Pinjar plantation study sites) was attributed to historical climate and groundwater trends.

A preliminary desktop study was undertaken with the aid of a Geographic Information System (using ESRI ArcView 3.2). Pine stand characteristics such as planting date, planting density, and silvicultural records (thinning, fertiliser application and fire treatments) were integrated with depth to groundwater levels for 2003. These were unpublished records obtained from the Forest Products Commission. Study sites were identified by building a query expression addressing the three age classes, and the two depth to groundwater criteria listed above. Additional verification of groundwater trends was performed by cross-checking the depth to groundwater dataset with groundwater monitoring data maintained by the Department of Environment (2004).

2.3 Site details

As a result of the desktop study and a subsequent field visit, seven stands of pine were selected to represent the three age classes, and two groundwater regimes (Table 2-1). Four shallow groundwater stands (GN1991, GN1985, GN1965a and GN1965b) were located at the eastern extent of the Gnangara plantation (latitude 31.75S and longitude 115.95E; ~59 mAHD), and three deep groundwater stands (PJ1995, PJ1982, and PJ1971) were located ~25 km northwest (latitude 31.60S and longitude 115.85E; ~62 mAHD) in the Pinjar plantation (Figure 2-1). Within the Pinjar and Gnangara plantations the stands of differing age classes were generally located within 300 m of each other. The exception was site GN1965a, located approximately 1.5 km northeast of the other Gnangara sites (Figure 2-3).

Table 2-1: Site classification matrix indicating the depth to groundwater regime and stand-age characteristics selected to evaluate correlations between growth trends and $\delta^{13}C$, and historical climate and groundwater trends of *Pinus pinaster* Ait. The prefix indicates the plantation area (i.e. GN = Gnangara plantation, and PJ = Pinjar plantation) and numerical suffix denoting planted date.

	Depth to Groundwater	
Stand Age	Shallow (<5 mbgl)	Deep (>20 mbgl)
<15 years	GN1991 (block F14A)	PJ1995 (block B38B)
15-25 years	GN1985 (block 128A)	PJ1982 (block C14C)
>25 years	GN1965a (block F6) GN1965b (block F13)	PJ1971 (block B7A)

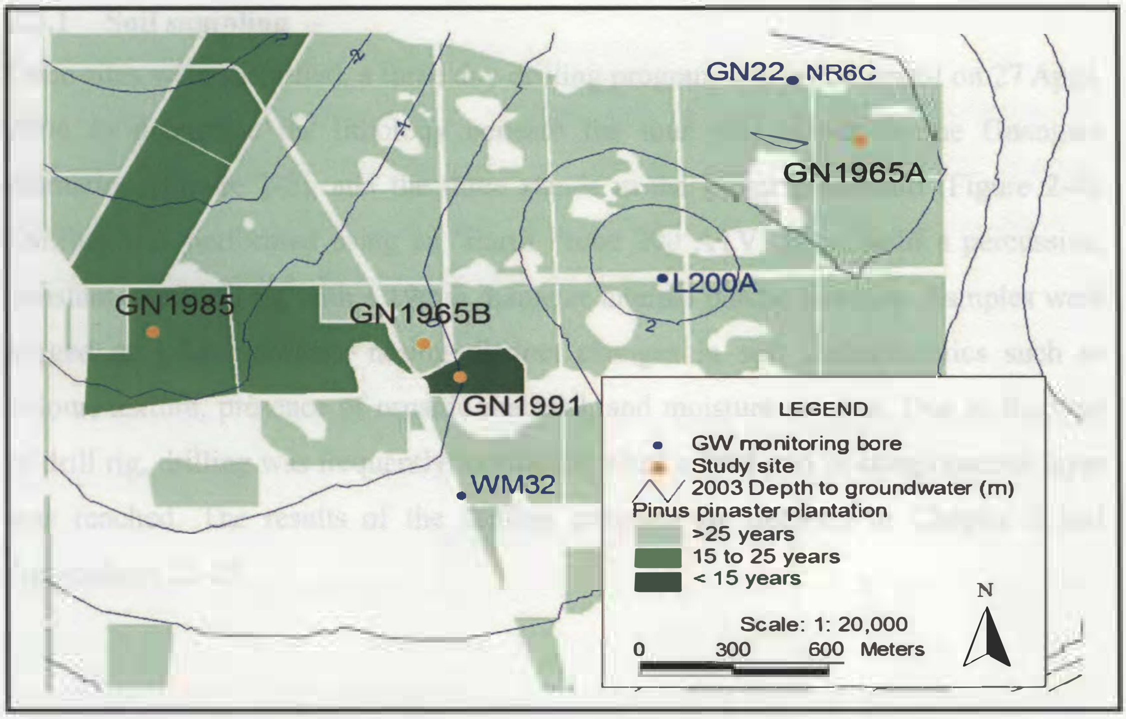

Figure 2-3: Gnangara plantation study sites representing stands of *Pinus pinaster* Ait with access to groundwater resources (<5 mbgl). Site GN1991 represents the young age class (<15 years), GN1985 the intermediate age class (15-25 years) and GN1965a and GN1965b the old age class (>25 years). Data for map production sourced from the Forest Products Commission (map produced by the author).

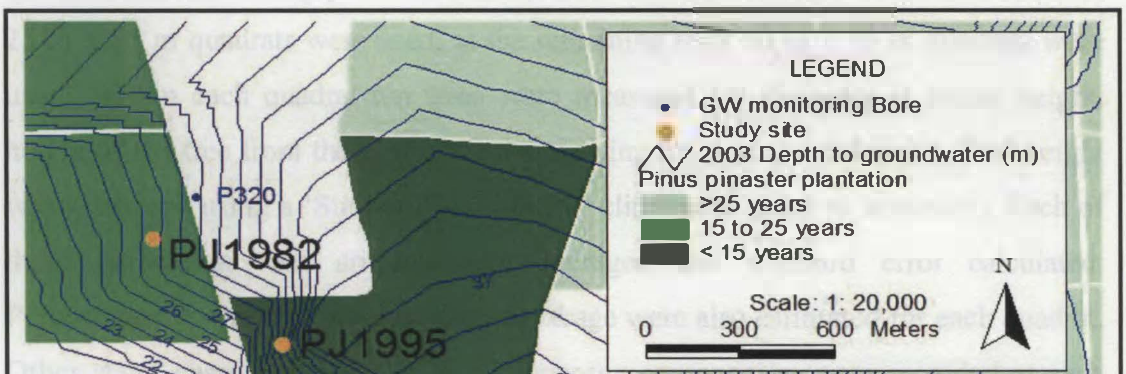

Figure 2-4: Pinjar plantation study sites representing stands of *Pinus pinaster* Ait without access to groundwater resources (>20 mbgl). Site PJ1995 represents the young age class (<15 years), PJ1982 the intermediate age class (15-25 years) and PJ1971 the old age class (>25 years). Data for map production sourced from the Forest Products Commission (map produced by the author).

2.3.1 Soil sampling

Once sites were identified, a three day drilling program was commenced on 27 April, 2004 to determine the lithology beneath the four pine stands in the Gnangara plantation (Figure 2-3), and the three stands in the Pinjar plantation (Figure 2-4). Drilling was performed using an 'Earth Probe 200 ATV' fitted with a percussive, constant core drill rig with a 19mm diameter internal plastic sleeving. Samples were logged at 1.2m intervals, noting distinct changes in soil characteristics such as colour, texture, presence of organic material, and moisture content. Due to the type of drill rig, drilling was frequently terminated when a hard-pan or conglomerate layer was reached. The results of the drilling program are detailed in Chapter 3 and Appendices 22-28.

2.3.2 Forest stand attributes

Forest stand characteristics were measured using standard forest mensuration techniques (Husch, Miller, & Beers, 1982). Within each of the seven stands, three quadrats were randomly placed. At three of the sites (GN1991, GN1985 and PJ1995) 25 m x 25 m quadrats were used, at the remaining sites 50 m x 50 m quadrats were used. Within each quadrat ten trees were measured for diameter at breast height, height of the tree from the ground to the growing tip, and stand density. Tree height was measured using a 'Suunto PM-5/360PL' clinometer (±0.5 m accuracy). Each of these parameters was arithmetically averaged and standard error calculated. Percentage crown cover and leaf litter coverage were also estimated for each quadrat. Other stand characteristics such as understorey composition were recorded at each site. The stand characteristics and the attributes of the sampled trees are detailed in Chapter 3.

2.4 SITE SELECTION LIMITATIONS

The nature of forest management practices and the heterogeneity of site-specific geology and hydrology features made it impractical to select sites with identical characteristics. The following is a brief summary of the limitations and assumptions made when determining appropriate sites for this study.

The Bassendean Dune Complex of the Gnangara sites are characteristically highly leached and nutrient poor (Seddon, 1972). The nutrient levels of the younger soils of the Spearwood Dune Complex are slightly elevated in comparison (Butcher, 1979). The difference in soil nutrients may contribute to different growth trends (Hopkins, 1960), and $\delta^{13}C$ values (Guehl, Fort, & Ferhi, 1995; Brooks, Flanagan, Varney, & Ehleringer, 1997). Soil nutrients were not assessed however nitrogen concentrations were analysed from foliar material collected from sampled trees (see Chapter 4). Therefore foliar nitrogen was used as an indirect measure of soil nutrient levels (Butcher, 1979).

The geology of the study sites were evaluated by drilling one bore hole per site. The interpretation of growth trends and $\delta^{13}C$ based upon one soil sample is problematic. Thus care was taken not to overestimate the influence of site-specific geology upon growth trends and $\delta^{13}C$ values.

Site-specific historical groundwater records were not available, however due to the economic, social and environmental value of the groundwater resources of the Gnangara Mound there were sufficient bores located near to the study sites to infer the groundwater conditions.

Forest disturbances caused by drought deaths (Havel, 1968), insect attack (Rayner, 1992) and thinning programs (Butcher & Havel, 1976) frequently result in an increased availability of light, nutrient and water resources (Warren, McGrath, & Adams, 2001). Therefore dissimilarity in thinning regimes between sites may differentially influence water availability, growth trends and $\delta^{13}C$. A number of

methods were implemented to minimise the effects of endogenous disturbances, these will be dealt with in detail in Chapter 3.

Genetic improvements were progressively made to *Pinus pinaster* Ait. seed stock, particularly after 1972 (Butcher & Hopkins, 1993) hence it is plausible that growth rates of younger, genetically improved stands may be enhanced. Unfortunately records of seed stock for each stand were not available, although it was likely that genetic differences within selected age classes would be minimal, therefore it is appropriate to compare growth trends within age classes over time. Other techniques such as standardisation are available (see section 3.4.5) to convert growth trends to dimensionless indices to make comparison between different genetic progenies possible.

The presence of an understorey stratum can make a significant contribution to depletion of soil moisture in the upper soil profile (Farrington *et al.*, 1989; Dodd & Bell, 1993). The understorey composition in the Pinjar plantation was more diverse and contained some deep rooted perennial species such as *Eucalyptus* sp. and *Banksia* sp. (see Chapter 3); however the proportion of space occupied by these species was similar to those of the Gnangara plantation sites, therefore the understorey was anticipated to equally influence water availability at both study sites.

CHAPTER 3: GROWTH OF *PINUS PINASTER* AIT. IN RELATION TO HISTORICAL CLIMATE, AND GROUNDWATER TRENDS

3.1 INTRODUCTION

Data derived from dendrochronology research have played a vital role in the reconstruction of historical climate (Briffa, 2004; Martinelli, 2004). Traditionally, isolated trees located in water limited conditions, such as those found in boreal forests, are selected for dendrochronology studies (Schweingruber, 1988). These conditions reduce the effect of other factors influencing growth such as competition for light, nutrient and water resources thereby enhancing the strength of the climate signal represented in the tree growth-rings.

The selection of species for chronology development is critical (February & Stock, 1998a). Suitable species should have distinct seasonal or annual growth rings with strong growth responses to environmental change (Stokes & Smiley, 1968). The suitability of conifers is high and they are frequently selected for the reconstruction of historical rainfall and temperature regimes throughout North America, Europe, and Russia (Briffa, 2004; Martinelli, 2004). The majority of dendrochronology research is focused upon tree species within temperate regions. This was based upon the assumption that trees in tropical regions grew all year round and do not produce annual growth rings, conversely trees in arid climates were deemed unsuitable due to the influence of poorly defined seasons upon ring formation (Schweingruber, 1988).

More recently a number of studies have identified species occurring in tropical and arid climates which produce discernable annual growth rings, making them suitable for chronology development. Worbes (1999), for example, assessed 37 species from the Caparo Forest Reserve in Venezuela and identified that many of these produced distinct annual growth rings. Stahl *et al* (1999) found that *Ptetocarpus angolensis* from Zimbabwe produce annual growth rings. February and Stock (1998b) successfully dated growth rings of *Widdringtonia cedarbergensis* and verified the potential for applications in climate reconstruction in a Mediterranean climate in South Africa.

In Western Australia, there have been few dendrochronology studies due to the paucity of long-lived tree species with distinct annual growth rings. Rayner (1992) was able to estimate the age of karri (*Eucalyptus diversicolor*). The longest tree-ring chronology was developed by Dunwiddie and LaMarche (1980) of *Callitris preissii* near Perth, dating from 1931 to 1975. The establishment of exotic plantations in recent decades however has provided new opportunities for the application of dendrochronology techniques to evaluate the influence of climate and water availability upon growth trends.

Eric Hopkins (1999b) used dendrometer bands over three years to evaluate the influence of climate and thinning regimes upon growth trends of *Pinus pinaster* Ait. stands occurring in the Gnangara plantation. The bands were measured at 7 to 10 day intervals and daily average minimum and maximum temperature, rainfall and evaporation and sunlight were recorded. A single recording dendrometer was also used with additional data collected including relative humidity and soil moisture deficit. The study found that there was a significant correlation between growth and the maximum and minimum temperature in an unthinned plot (2471 s/ha^{-1}) and that evaporation was important in the thinned plots (247 and 990 s/ha^{-1}). Rainfall was found to significantly contribute to growth, however only when soil moisture was limiting. In the thinned plots annual growth was minimal from January to May, and began to increase in June-July, and peaked in September-October. In the unthinned plots the period of increased growth was delayed by up to two months due to the enhanced depletion of soil moisture as a consequence of stocking density (Hopkins, 1999b).

The influence of climate, soil moisture trends, and silviculture treatments upon growth of *Pinus pinaster* Ait. stands on the Gnangara Mound is well documented (Butcher & Havel, 1976; Butcher, 1977; Hopkins, 1999b), yet it is not certain whether pine stands underlain by shallow groundwater directly access this resource.

The objectives of this study were to apply dendrochronology techniques to evaluate the growth trends of *Pinus pinaster* Ait. stands occurring on the Gnangara Mound. These growth trends were then related to historical climate and long-term groundwater trends. This study was designed to address the hypothesis that there is no significant difference in growth trends between trees which potentially have

access to groundwater resources (<5 metres below ground level), and those which do not (>20 mbgl).

Specific objectives are as follows:

i. To evaluate the influence of historical climate upon interannual growth trends of *Pinus pinaster* Ait.

ii. To evaluate the influence of shallow groundwater (<5 mbgl) resources upon growth trends of *Pinus pinaster* Ait. by comparing them with stands with deep groundwater (>20 mbgl) resources.

3.2 PINUS PINASTER PHENOLOGY

The growth trends and phenology of *Pinus pinaster* Ait. were described in detail by Hopkins (1999a). Generally growth over the first 3-5 years is slow, then rapid for the following five years. After this period as stand competition increases, growth decreases. This trend continues unless management strategies are implemented to reduce competition for resources such the application of phosphorous-based fertilizers and the reduction of stand density through thinning programs (Butcher, 1977, 1979).

Major bud flush corresponds to the more favourable soil moisture conditions present in late July reaching the maximum in mid to late August, the majority of height growth occurs between June and November (Hopkins, 1999a). Earlywood tracheids are formed during this period and are characterised by circular inner apertures and circular bordered pits (Esau, 1977). As soil moisture availability decreases in early summer, latewood tracheids begin to form. These can be distinguished from earlywood cells since they have oval inner apertures, reduced borders and thicker cell walls (Esau, 1977). Latewood cells are consequently denser than earlywood and appear darker in colour. Thus the characteristics of annual growth-rings, in particular the proportion of earlywood and latewood, can be used to reconstruct environmental conditions existing during ring formation.

3.3 SITE CHARACTERISTICS

The Gnangara study sites are underlain by shallow groundwater resources (<5 metres below ground level) while the Pinjar sites represent deep groundwater conditions (>20 mbgl). The general site characteristics and methodology used to measure site specific characteristics are described in Chapter 2. The geology, hydrology and forest stand attributes for each site are described in detail in the following sections. The bore logs recorded during the drilling program are contained in Appendices 22-28.

3.3.1 Geomorphology

The intrusive soil sampling program revealed that the geology of the Gnangara study sites are typical of poorly drained areas of the Bassendean Dune Complex (McArthur & Bettenay, 1960). With the exception of GN1965b the lithology beneath the Gnangara stands are humus podzols characterised by white/grey sands in the upper profile underlain by mottled sands and a humus or calcrete hardpan at ~2.5 metres below ground level (mbgl). Dry white/grey sands continue throughout the soil profile at site GN1965b to a depth of 2.8 m, where a brown hardpan layer is evident. The capillary fringe was determined at sites GN1985, GN1965a at 3.4 mbgl and 2.5 mbgl respectively. Based upon groundwater records from nearby bores (Department of Environment, 2004) the capillary fringe beneath sites GN1991 and GN1965b are expected to occur at depths less than 5 metres below ground level (mbgl).

The geology of the Pinjar sites is typical of the Spearwood Dune Complex with deep yellow sands throughout the profile (McArthur & Bettenay, 1960). Generally, soil moisture increases with depth at all sites. An impeding sandstone layer was evident ~8.5 mbgl at site PJ1995 however moisture levels did not appear to increase significantly until depths greater than 9 mbgl (Appendix 26). Groundwater records from nearby bores (Department of Environment, 2004) indicate that the capillary fringe is likely to occur at depths greater than 20 mbgl.

3.3.2 Historical climate

Climate data required in order assess the influence of historical climate upon growth trends for each of the sites was obtained from the Bureau of Meteorology's regional weather stations including Pearce, Wanneroo, Cowalla, Yanchep, Marginiup, Gnangara and Gnangara Park (Bureau of Meteorology, 2003, 2004b, 2004a), and interpolated data sourced from the SILO Data Drill. The latter dataset was provided under license from the Queensland Department of Natural Resources and Mines (2004).

Perth's records date back to 1876 and is the only weather station with complete, long-term climate data. Data from the aforementioned weather stations was either incomplete, did not represent the period from 1965 to 2004 or was limited to just rainfall data rather than the required attributes such as temperature and evaporation. Using SILO modelled data (Queensland Department of Natural Resources and Mines, 2004), and Perth climatic data (Bureau of Meteorology, 2004b), the average rainfall of the Pinjar study sites since 1965 was estimated to be 5% less than the Perth records (Figure 3-1).

Data from the SILO data drill is modelled from primary data sourced from the Bureau of Meteorology (Queensland Department of Natural Resources and Mines, 2004). Given the spatially and temporally inconsistent nature of data recorded at the various meteorological stations (as described above) the use of SILO data may introduce an element of error which may differentially influence the study sites.

Consequently the climate data from the Perth weather station was deemed the most appropriate for identifying the influence of climate upon growth trends. Analysis of growth response to climate can be enhanced with the use of site specific weather stations however these were not available for this study.

Since the main growing period for *Pinus pinaster* Ait. in Western Australia is from June to November (Hopkins, 1999a, 1999b), all annual climate data were recalculated to represent the growing season from April to March of the following year.

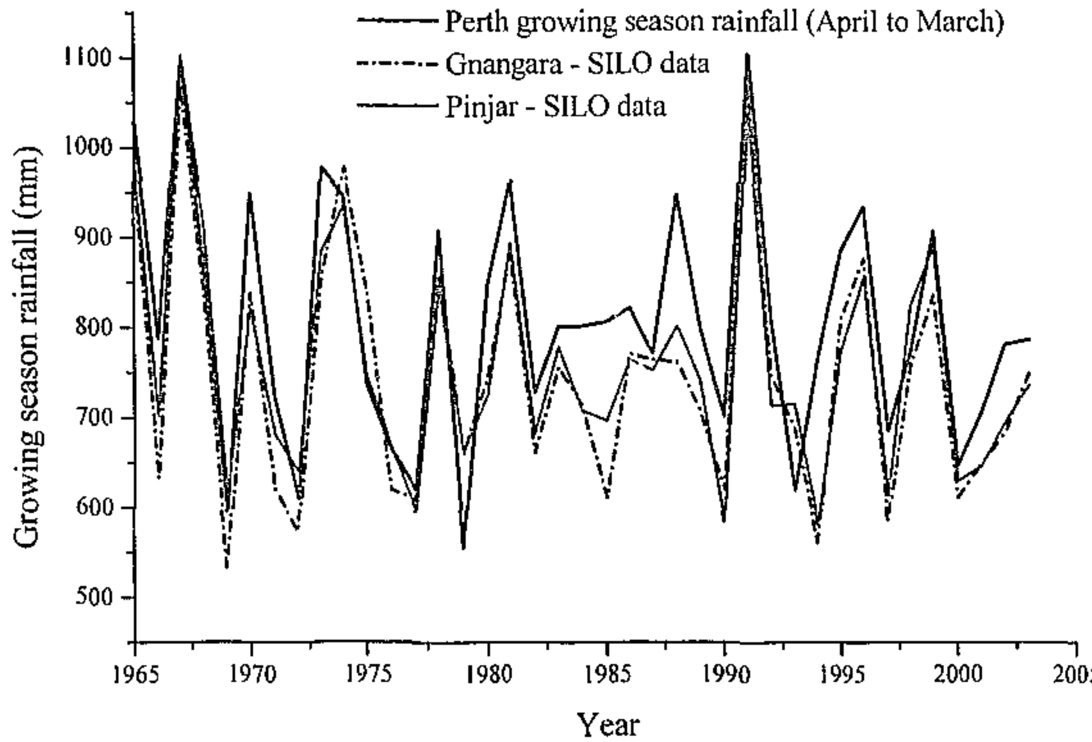

Figure 3-1: Growing season (April to March) rainfall trends from 1965 to 2003. These were sourced from the Perth regional office (Bureau of Meteorology, 2004b) and modelled data from the SILO data drill for Gnangara and Pinjar (Queensland Department of Natural Resources and Min' s, 2004).

3.3.3 Groundwater trends

The groundwater resources of the Gnangara Mound are of high environmental and economic value (Welker Environmental Consultancy, 2002), hence extensive groundwater data are collected. Figure 3-2 plots the groundwater trends recorded near to the study sites at the Gnangara and Pinjar plantations. Groundwater monitoring bores L200A and WM32 were used to evaluate the historical groundwater trends of sites GN1991, GN1985, and GN1965b (Figure 3-2). Annual average groundwater levels of both bores fluctuated over time with peak levels occurring during 1986, 1992 and 1999, and the lowest levels occurred in 1990 and after 2001. The greatest decline was recorded at bore WM32 where average annual water levels fell from 4.1 mbgl to 5.1 mbgl between 2000 and 2001, and dropped to 5.8 mbgl in 2003.

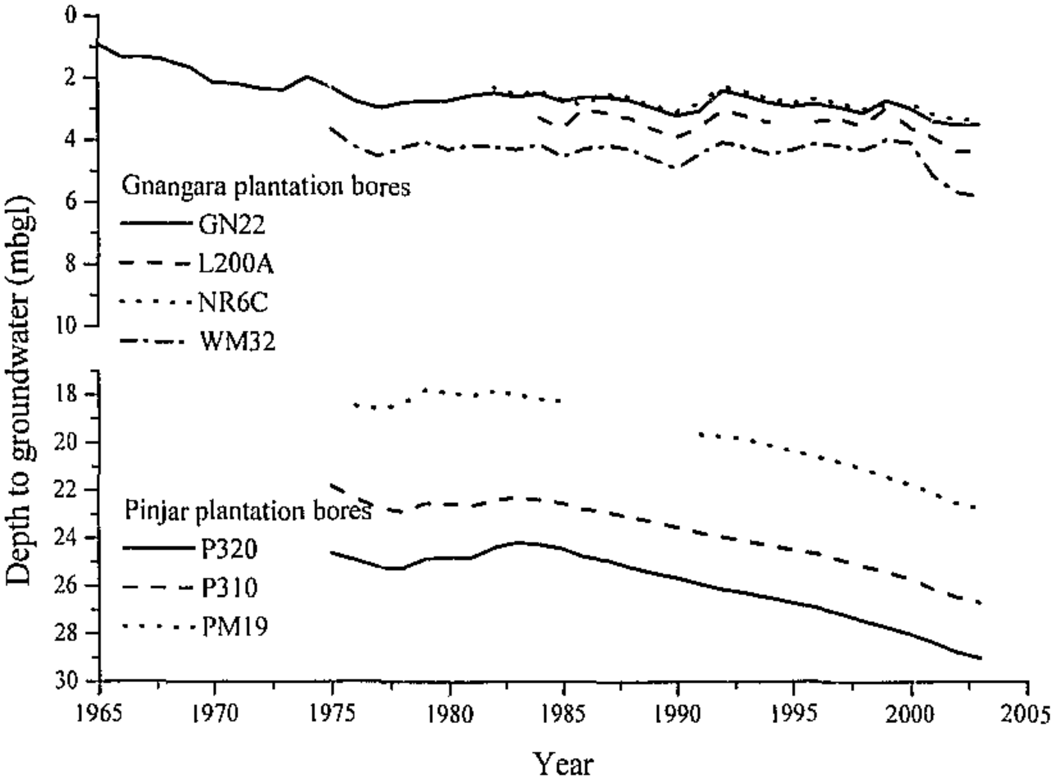

Figure 3-2: Time-series of the mean annual depth to groundwater trends of five groundwater monitoring bores located nearby the Gnangara plantation sites (GN22, L200A, L200C, NR6C, and WM32) and four nearby the Pinjar sites (PM320, P210, PM19, and PM17). Noting that the sampling frequency of each bore was variable over time. Unpublished data sourced from the Department of Environment (2004).

Bores GN22 and NR6C were used to evaluate groundwater trends for site GN1965a. Groundwater trends of these bores are similar to L220A and WM32 with the greatest declines occurring after 2001. Generally, the groundwater trends of these bores declined over time however the annual mean remained less than 3.5 mbgl during the monitoring period.

Groundwater monitoring bores P320, P210, and PM19 were used to evaluate the historical groundwater trends for the sites PJ1995, PJ1982 and PJ1971 (Figure 3-2). The general trends of these bores are best described as fluctuating between 1975 until 1985, thereafter groundwater levels at all of these bores started to decline at an average rate of 0.2 m per year. The water levels recorded at PM19 were ~18 mbgl from 1976 until 1985. Data from this bore are missing for the period from 1986 to 1990 therefore they were excluded from statistical analysis. After 1994, annual average depth to groundwater levels at all Pinjar site bores was greater than 20 mbgl.

3.3.4 Forest Stand Attributes

The following information is a compilation of forest stand attributes of the seven study sites measured in April, 2004 (see Chapter 2), and unpublished historical records maintained by the Forest Products Commission. Four trees were destructively sampled in each of these sites; the attributes of these are detailed in section 3.5 (Table 3.2).

A planting density of ~2000 stems per hectare was most common, particularly for stands occurring in the Gnangara plantation (Table 3.1). The lowest planting density was site PJ1982 at 1042 s/ha^{-1}, followed by PJ1995 and PJ1971 at 1984 s/ha^{-1}. The planting density of sites GN1985, GN1965A and GN1965B were all 2315 s/ha^{-1}. GN1991 was the greatest at 3086 s/ha^{-1}.

Single thinning events occurred at stands PJ1982 and PJ1971 reducing stand densities to 152 s/ha^{-1} and 234 s/ha^{-1} respectively (Table 3.1). Multiple thinning events occurred at GN1965a and GN1965b reducing the stand densities to 150 s/ha^{-1} and 121 s/ha^{-1} respectively. There are no records of thinning operations occurring at three sites (GN1991, GN1985, and PJ1995); therefore changes to stand density over time are attributed to natural thinning processes or removal of younger trees for sale as Christmas trees (C. Sanders, pers. comm. 3 May, 2004). The final stand density of these stands is 2410 s/ha^{-1}, 1066 s/ha^{-1} and 624 s/ha^{-1} respectively.

In the main, the sites located in the Gnangara plantation have higher stand densities, hence higher proportions of crown cover (Table 3.1). The young Pinjar stand (PJ1995) in particular has an open canopy with an estimated crown cover of 25%. The next highest canopy cover is found at site PJ1982 (30%), followed by PJ1971 (40%). The two old sites (GN1965a, 1965b) in the Gnangara plantation have a crown cover of 50%, the next highest at site GN1991 (60%) and the highest found at site GN1985 (70%). With the exception of GN1991 and GN1985 all other sites are interspersed with forestry tracks therefore projected crown cover in these sites is more variable.

Average tree heights were positively related to tree age with the greatest average tree heights measured at sites GN1965a (22.95 m) and GN1965b (22.3 m) (Table 3.1). In sequential order from next tallest to shortest was PJ1971 (18.88 m), PJ1982 (16.41 m), GN1985 (14.50 m), GN1991 (12.53 m), then PJ1995 (8.63 m).

Trends for the mean tree diameter at breast height over bark (dbhob) corresponded to tree height (Table 3.1). The greatest average diameter (dbhob) was recorded at site GN1965b (47.16 cm), then in sequential order from next broadest to thinnest was GN1965a (45.79 cm), PJ1971 (37.83 cm), PJ1982 (35.16 cm), GN1985 (22.77 cm), PJ1995 (18.05 cm) then GN1991 (16.04 cm).

The stand basal areas for each site were calculated as described in Husch *et al* (1982). With the exception of site PJ1971, stand basal area correlated with stand density trends. The highest basal area was recorded at site GN1991 (49.5 m^2/ha^{-1}), the youngest stand in the Gnangara plantation (Table 3.1).Then in sequential order from next largest basal area to smallest was site GN1985 (44.0 m^2/ha^{-1}), PJ1971 (26.5 m^2/ha^{-1}), GN1965a (25 m^2/ha^{-1}), GN1965b (21.4 m^2/ha^{-1}), PJ1995 (16.1 m^2/ha^{-1}), then PJ1982 (14.9 m^2/ha^{-1}).

Stand volume was calculated by multiplying the stand basal area using the calculation (Husch *et al.*, 1982):

<u>Total volume = Basal area over bark x Form factor x Height</u>

The form factor of 0.38 was used for stands with an over bark diameter at breast height (dbhob) less than 20cm, and 0.34 for stands greater than 20cm dbhob (P. Ritson, pers. comm., 4 October, 2004). The largest stand volume was recorded at site GN1991 (235.6 m^3/ha^{-1}), then in sequential order from next largest stand volume to smallest was GN1985 (220.8 m^3/ha^{-1}), GN1965a (197.7 m^3/ha^{-1}), PJ1971 (170.9 m^3/ha^{-1}), GN1965b (163.6 m^3/ha^{-1}), PJ1982 (83.3 m^3/ha^{-1}), then PJ1995 (51.9 m^3/ha^{-1}).

Generally all stands lack an understorey stratum, particularly beneath those occurring on the nutrient poor Bassendean sands of the Gnangara plantation. Understorey in this region is typically composed of *Xanthorrhoea preissii, Macrozamia riedlei,* and

exotic weeds covering less than 5% of the forest floor, the remainder is covered with dense leaf litter and coarse woody material (Table 3.1). GN1991 and GN1985 were also interspersed with *Melaleuca* sp. which are indicative of moist soil conditions (Havel, 1968).

The understorey composition beneath the Pinjar stands also comprises less than 5% of the forest floor but is more diverse than the Gnangara plantation. The understorey in this region consists of *Xanthorrhoea preissii*, *Macrozamia riedlei*, *Banksia attenuata*, *Hybbertia hypericoides*, *Hardenbergia comptoniana*, *Eucalyptus* sp., *Acacia* sp., *Oxylobium* sp, and *Drosera* sp. Leaf litter accounts for ~30% of the forest floor, the remainder being comprised of course woody material from thinning operations, bare sand and exotic weeds (Table 3.1).

Table 3.1: Forest attributes measured in April 2004, historical records, and silvicultural treatments for seven stands of *Pinus pinaster* Ait. occurring on the Gnangara Mound. Four sites were located in the Gnangara plantation, the remaining three in the Pinjar plantation. The prefix indicates the plantation area (i.e. GN = Gnangara plantation, and PJ = Pinjar plantation) and numerical suffix denoting planted date. All figures in brackets represent standard error.

	Gnangara plantation (<5m to groundwater)				Pinjar plantation (>20m to groundwater)		
	GN1991	GN1985	GN1965a	GN1965b	PJ1995	PJ1982	PJ1971
Planted year	1991	1985	1965	1965	1995	1982	1971
Planting stand density (s/ha^{-1})	3086	2315	2315	2315	1984	1042	1984
Thinning event	None	None	1981, 1991	1984, 1991	None	1998	1993
Mean stand density 2004 (s/ha^{-1})	2410 (±0.04)	1066 (±0.03)	150 (±0.04)	121 (±0.04)	624 (±0.02)	152 (±0.05)	234 (±0.02)
Mean Height (m)	12.53 (±0.2)	14.50 (±0.7)	22.95 (±0.3)	22.30 (±0.3)	8.63 (±0.1)	16.41 (±0.3)	18.88 (±0.2)
Mean Over Bark Diameter (cm)	16.04 (±0.4)	22.77 (±0.5)	45.79 (±0.8)	47.16 (±0.8)	18.05 (±0.3)	35.16 (±0.6)	37.83 (±0.4)
Calculated stand basal area (m^2/ha^{-1})	49.5	44.0	25.0	21.4	16.1	14.9	26.5
Calculated stand volume (m^3/ha^{-1})	235.6	220.8	197.7	163.6	51.9	83.3	170.9
Projected crown cover (%)	60%	70%	50%	50%	25%	30%	40%
Percentage leaf litter (%)	95%	95%	95%	95%	25%	25%	40%
Fertiliser application event	7/2000	None	12/1971, 6/1982, 9/1993, 7/2000	12/1971, 6/1985, 9/1993, 7/2000	None	10/1992, 6/1994, 7/2000	6/1994
Fire event	None	None	1980, 1985, 1990, 1994, 1998, 2002	1980, 1985, 1990, 1994, 1998, 2002	None	1998, 2001	1986, 1992, 1996, 2000

Phosphorus-based fertilizer products were applied by hand around the base of trees after planting and subsequent applications generally would have been broadcast (S. Wood pers. comm. 22 March, 2004). The timing and rate of application for each site was variable (Table 3.1). At the Gnangara plantation sites GN1991 had 150 kg/ha^{-1} of double-superphosphate applied in 2000. There are no records for GN1985. Site GN1965a had 450kg/ha^{-1} of an unknown fertiliser in 1971, 500 kg/ha^{-1} of an unknown fertiliser in 1982, 250 kg/ha^{-1} of double-superphosphate in 1993, and 150kg/ha-1 of double-superphosphate applied in 2000. Site GN1965b had 450 kg/ha^{-1} of an unknown fertiliser in 1971, 500 kg/ha^{-1} of superphosphate in 1985, 250 kg/ha^{-1} of double-superphosphate in 1993, and 150 kg/ha^{-1} of double-superphosphate applied in 2000.

For the Pinjar plantation sites (Table 3.1) there are no records of fertiliser application at site PJ1995. Site PJ1982 had 250 kg/ha^{-1} of double-superphosphate applied in 1992, 150 kg/ha^{-1} of double-superphosphate in 1994, and 150 kg/ha^{-1} of double-superphosphate in 2000. At site PJ1971 there are records of one application of 150 kg/ha^{-1} of double-superphosphate occurring in 1994.

Prescribed burning of leaf litter and coarse woody material commenced 15-16 years after planting date at four sites; these being sites GN1965a, GN1965b, PJ1982 and PJ1971 (Table 3.1). Regular burning of each of these sites continued at 4-5 year intervals. There are no records of prescribed burning in the remaining sites (GN1991, GN1985, and PJ1995).

3.4 MATERIALS AND METHODS

3.4.1 Tree selection

Four trees were sampled within each of the seven sites. Each tree was located at least five rows or 50 m from the nearest logging track to reduce the edge effect. This reduced the influence of factors such as changes to water availability due to the presence of graded or compacted surfaces, and the effects of dust upon rates of photosynthesis. Dominant trees positioned in a relatively open canopy were selected to minimise the influence of competition for resources, so as to maximise the strength of the climate signal (Fritts, 1976). Dominance class was subjectively assessed upon tree height and diameter at breast height. Due to practical limitations (i.e. economic return for sampled trees) all trees were located relatively close to each other (~25 m apart). At each of the seven sites the basic attributes of height, diameter at breast height, and stem sample height were recorded for each of the four sampled trees. Three foliar samples were removed from the northern aspect of each tree representing the lower, middle and upper strata for analysis of $\delta^{13}C$ and nitrogen concentrations (see Chapter 4).

3.4.2 Sample preparation

The position of a tree in the landscape (such as slope, aspect, and exposure to prevailing winds etc), or changes to the structure of the tree (such as loss of branches) may create an unbalanced load leading to the development of compression wood (Esau, 1977). Consequently the characteristics of tree growth-rings may be variable across a tree's cross-section. Obtaining wood samples using incremental corers may not adequately represent these heterogenous characteristics (February & Stock, 1998b; Worbes, 1999). Therefore it was deemed appropriate to remove a whole cross-section from each of the four trees from the seven sites (n = 28).

Trees were felled at an average height of 37 cm (±3 cm) above ground level and a whole cross-section of approximately 7 cm (±0.3 cm) thick was removed (Table 3.2). Care was taken to ensure that whole cross-sections were removed between whorls, therefore reducing the influence of branch growth upon ring development. Each whole cross-section was air dried for two weeks before being oven dried at 40^0C for

a further two weeks. Preparation of samples for chronology development involved planing one horizontal surface with a 'Robland' 310mm buzzer, then sanding with a 76 x 533 mm belt sander commencing at 80 grit and graduating to 600 grit paper. Each whole cross-section was then marked in four directions with radii number 1 corresponding to magnetic north.

3.4.3 Tree growth-ring chronology development

The boundaries of each annual growth ring and the corresponding earlywood and latewood regions were delineated on the basis of colour and tracheid characteristics. These characteristics were distinguished using an 'Olympus SZC12' (12.86:1) stereo research microscope. Commencing at the northern azimuth (radii number 1) the widths of the four radii were measured using a 'Mituoyo' dial vernier calliper with an accuracy of 0.05 mm. The commencement of the latewood cells was often gradual hence the measurement of the individual latewood and earlywood measurements was less accurate than that for annual growth.

3.4.4 Cross dating tree growth-ring chronologies

Signature rings are exceptionally narrow or broad growth rings formed during periods of unusually low or high resource availability (Schweingruber, 1988). By cross-dating tree signature rings with known factors influencing growth, such as meteorological records, or known year of planting, the year of formation can be identified. Missing rings, convergent rings or the presence of false rings may lead to dating errors, therefore arguably one of the most important quality control procedures is to cross-check chronologies between trees (Fritts, 1976; Holmes, 1983; Schweingruber, 1988).

Tree growth-ring measurements from each tree were arithmetically averaged, converted to the Tucson Decadal format and imported into COFECHA, one of the most widely used programs for evaluating cross-dating and measurement accuracy of tree-ring chronologies (Grissino-Mayer, 2001). The default settings of COFECHA were selected. Measurements diagnosed by COFECHA as potentially erroneous (i.e.

outliers with greater than 3 standard deviations from the mean) were visually re-checked. This method proved an essential tool for identification of measurement errors, or cross-dating discrepancies prior to statistical analysis.

3.4.5 Standardising tree growth-ring chronologies

Trees unaffected by stand competition show age-related gradual declines in growth over time (Cook & Peters, 1981). These non-climatic, and competition related trends must first be reduced prior to quantifying correlations between growth and climate (Fritts, 1976; Briffa, 1987; Woollons & Norton, 1990). This process is termed standardisation, which produces a dimensionless index series with a mean value of one (Schweingruber, 1988). The traditional method of calculating standardised tree indices is achieved by fitting raw ring measurements with a modified exponential curve (Fritts, Mosimann, & Bottorff, 1969; Fritts, 1976).

The process of standardising tree growth-ring chronologies becomes more complex when investigating trees within closed-canopy forests subject to random and/or irregular disturbances, which may result in changed access to light, nutrients and water resources; this is referred to as white noise (Fritts, 1976). To reduce white noise an alternative approach using a smoothing spline can be used (Cook & Peters, 1981).

Standardised indices were produced by importing arithmetically averaged tree growth-ring measurements from each sample site into the computer program ARSTAN (V6.05P) (Cook & Holmes, 1999). A number of options were available for producing tree growth-ring chronologies, the most appropriate were determined through qualitative and quantitative assessment. Tree ring indices were computed as the robust mean value function of the detrended and standardised tree growth-ring series using a smoothing spline with a wavelength of 7 years.

3.4.6 Data analysis

The historical growth trends for the four study sites in the Gnangara plantation and three sites in the Pinjar plantation were analysed by graphically displaying the mean annual growth trends over time. The influences of historical silvicultural treatments were also evaluated at this point.

The climate occurring in the current year influences bud growth of the following year, whilst cambium growth is dependant upon the current years conditions (Lanner, 1985). To confirm this principle, linear regressions were performed between growth and Perth's growing season rainfall (April to March of following year). This was also performed using two and three year moving averages. Results indicated that there was little carry over effect therefore each year's growth was considered independent of the preceding year's rainfall.

Annual groundwater levels were derived for each site by averaging the annual groundwater levels of nearby bores (Department of Environment, 2004). Annual groundwater levels at site GN1965a were derived from records from bores L200A and NR6C; bores GN22 and WM38 were used at site GN1965b; and bores P310 and P320 used for the Pinjar sites. Records from bore PM19 were removed from the analysis as the data was incomplete.

Step-wise forward multiple linear regressions were performed to evaluate the influence of total rainfall and the mean, minimum, maximum and cumulative temperature, evaporation and groundwater levels upon annual growth trends of the three old stands (>25 years). All data were analysed using routines contained within the statistical packages Origin (V5.0) and SPSS (V11.5).

3.5 RESULTS

3.5.1 Attributes of sampled trees

The forest attributes of the four sampled trees from each site at the Gnangara and Pinjar plantations, such as height and diameter at breast height over bark (dbhob), corresponded to the mean stand attributes measured during the preliminary site assessment (see section 3.3.4). With the exception of site GN1991 the mean height of sampled trees was greater than the mean forest stand height (Table 3.2). With the exception of PJ1971 the diameter at breast height over bark was less than the stand average.

Table 3.2: Summary of the mean and standard error (in brackets) attributes measured for the trees destructively sampled from the sites located at the Gnangara (n = 16) and Pinjar plantations (n = 12). Tree height, diameter at breast height over bark (dbhob), and height from where each whole cross-section was removed were recorded at time of sampling. The number of rings and annual increment for each tree were measured during chronology development.

	Gnangara plantation				Pinjar plantation		
Sampled tree details	GN1991	GN1985	GN1965a	GN1965b	PJ1995	PJ1982	PJ1971
Mean Height (m)	9.90 (±0.4)	16.05 (±0.4)	23.32 (±0.8)	23.28 (±0.3)	8.64 (±0.4)	17.05 (±0.5)	19.75 (±0.4)
Mean dbhob (cm)	13.62 (±1.3)	21.46 (±0.7)	41.66 (±3.1)	46.53 (±2.6)	14.78 (±0.3)	31.04 (±0.6)	41.11 (±2.2)
Mean whole cross-section height (m)	0.63 (±0.05)	0.25 (±0.02)	0.41 (±0.03)	0.51 (±0.07)	0.24 (±0.02)	0.27 (±0.05)	0.33 (±0.04)
Mean number of counted rings	10.25 (±0.5)	16.00 (±0.0)	35.75 (±0.5)	37.50 (±0.3)	8.00 (±0.0)	20.25 (±0.3)	30.25 (±0.3)
Mean annual radial increment (mm)	4.60 (±0.4)	5.41 (±0.4)	4.55 (±0.2)	4.68 (±0.2)	7.46 (±0.5)	6.83 (±0.3)	5.28 (±0.2)

The greatest mean diameter at breast height over bark (dbhob) was measured at site GN1965b (46.53 cm), and then in sequential order from broadest to narrowest was GN1965a (41.66 cm), PJ1971 (41.11 cm), PJ1982 (31.04 cm), GN1985 (21.46 cm), PJ1995 (14.78 cm), then lastly GN1991 (13.62 cm) (Table 3.2).

A review of tree growth-ring characteristics revealed that site GN1965b (Table 3.2) recorded the greatest number of dated growth rings (37.50), then in sequential order from highest to lowest was GN1965a (35.75), PJ1971 (30.25), PJ1982 (20.25), GN1985 (16), GN1991 (10.25) and lastly PJ1995 (8). Typically the first two to three growth rings were unable to be delineated.

Tree growth-ring incremental growth declines with age (Fritts, 1976; Schweingruber, 1988), therefore it would be expected that the youngest trees would have the greatest average incremental growth. This model did not hold true for the growth characteristics for the Gnangara sites. The greatest mean annual radial incremental growth was measured at site PJ1995 (7.46 mm), then PJ1982 (6.83 mm), then in sequential order from greatest to lowest was GN1985 (5.41 mm), PJ1971 (5.28 mm), GN1965b (4.68 mm), GN1991 (4.6 mm) then lastly GN1965a (4.55 mm) (Table 3.2).

3.5.2 Juvenile phase of growth

Analysis of the tree growth-ring chronologies from Gnangara plantation sites (GN1991, GN1985, GN1965a, and GN1965b), revealed a relatively consistent pattern over the first ten years of growth. This pattern was characterised by a linear increase in growth in the first three to five years, followed by rapid decline in growth for the following five years. The growth signatures for the Pinjar plantation sites (PJ1995, PJ1982, and PJ1971) over the first ten years of growth were also observed to have a consistent trend however it differed from the Gnangara plantation sites. This trend was considered to represent the juvenile phase of growth as described by Hopkins (1999a).

3.5.3 Annual tree growth-ring incremental growth

Prior to standardisation and statistical analysis, the average tree growth-ring measurements were graphically illustrated and compared. The first two or three years ring growth were unable to be distinguished during chronology development, however it was anticipated that ring-width incremental growth during this period was relatively small (Hopkins, 1999a). Figure 3-3 represents an aged related cumulative annual diameter growth of all sampled sites. Generally there was a linear increase in diameter from date of planting until approximately fifteen years of age. After this period growth trends appeared to diverge.

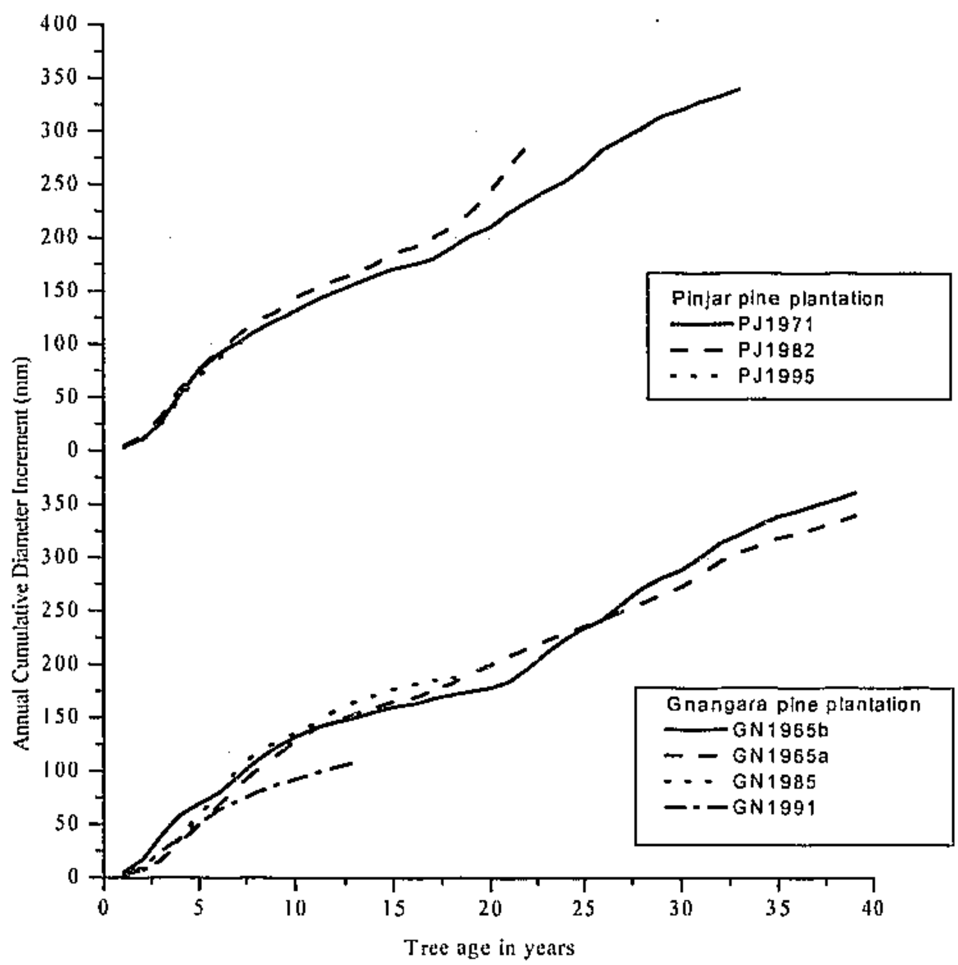

Figure 3-3: Relationship between age and mean cumulative annual incremental diameter growth of *Pinus pinaster* Ait. trees sampled from the Pinjar, and Gnangara plantations. The annual incremental diameter was calculated by doubling the mean annual radial increment commencing at the pith and terminating at the bark of four replicate samples from seven sites (n = 28). The true age of the pith ring was estimated from the curvature and growth trend of the 10 innermost rings.

3.5.4 Annual tree growth-ring incremental growth and the influence of silvicultural treatments

As was described previously, generally the first ten years of growth were characteristic of a juvenile phase of growth. After this period growth generally continued to decline until a silvicultural treatment such as thinning was applied. Increased growth generally followed these treatments however enhanced growth dissipated in less than three years after treatment. The influence of subsequent silvicultural treatments appeared to decrease over time. Increased periods of growth were observed during certain years or periods at multiple sites, irrespective of silvicultural treatment application. This was particularly evident in 1996 at sites GN1985, GN1965a, GN1965b, PJ1982, and PJ1971. Analysis of the influence of historical climate and groundwater trends is detailed in section 3.5.5.

A consistent trend of an increasing proportion of latewood corresponded to temporal changes to competition for resources as each stand developed or approached canopy closure; i.e. decreases to nutrient and water availability result in a shorter period of earlywood development and extended period of latewood development. The site-specific growth trends are detailed below.

At site GN1965a (Figure 3-4), the first ring measurements commenced in 1967, two years after planting date. In 1967 the growth ring measured 10.3 mm and increased to 12.2 mm in 1968. A gradual decline in growth commenced after this period and continued until 1980. This decline was most notable after 1974. The application of fertilizer in 1971 did not appear to enhance growth during this period. A prescribed fire event occurred in 1980, followed by thinning operation in 1981 and the application of fertilizer in 1982. From 1980 to 1983 there was increased ring growth from 2.2 mm to 4.5 mm. A prescribed fire occurred in 1985 however this did not appear to influence growth trends as they continued to decline from 1983 to 1990. In 1990 a prescribed fire occurred, followed by a thinning event in 1991, application of fertilizer in 1993 then another fire in 1994. Growth increased from 3.0 mm in 1990 to 4.0 mm in 1991, however began to decline again until 1994. A period of advanced growth occurred in 1995 and 1996 (>5.9 mm), however this declined rapidly again in 1997 to 3.7 mm. A prescribed fire event in 1998 was followed by a fertilizer application in 2000 and another prescribed fire event in 2002. With the exception of

1999 a general decline in growth occurred until 2001. After this period, growth increased slightly.

Latewood in 1967 (Figure 3-4) at site GN1965a accounted for 8% of the annual growth ring. After 1967 the proportion of latewood increased in a linear fashion to over 28% in 1973. The proportion of latewood increased steadily to over 40% in 1981. After this period the latewood proportion appeared to consistently fluctuate between 35-50%. The greatest fluctuation occurred in 1990 where the latewood accounted for less than 35%, then in 1991 where latewood accounted for 54% of the annual growth ring.

At site GN1965b (Figure 3-5), the growth ring measured 6.3 mm in 1966, one year after planting date. Growth increased to 10.9 mm in 1967. From 1968 to 1970 ring growth declined from 9.5 mm to 4.6 mm. The application of fertilizer in 1971 coincided with an increased ring growth in the following two years. A gradual decline in growth commenced after this period and continued until 1984. A prescribed fire event occurred in 1980 which appeared to slightly influence growth in 1981. From 1984 to 1987 there was an enhanced incremental growth from 1.9 mm to 7.2 mm. This coincided with a thinning event in 1984, and a prescribed fire event and application of fertilizer in 1985. From 1987 to 1999, growth trends appeared to respond to the various silvicultural treatments with peaks occurring in 1992 and 1996. These peaks were generally two years after a prescribed fire event however it was difficult to ascertain whether fire alone was responsible as other treatments occurred during this period. After successive growth peaks, each decline appeared to be more enhanced. The decline after 1987 took three years, two years after 1991 and one year after 1996. Growth increased slightly from 1997 to 1999, however continued to gradually decline until 2002. Growth was elevated slightly to 3.2 mm in 2003. The growth trends at site Gn1965b indicated that this site was more responsive to silvicultural treatments, particularly thinning treatments, than site GN1965a.

Latewood in 1966 (Figure 3-5) at site GN1965b accounted for 17% of the annual growth ring, then 7.5% in 1967. After 1967 the proportion of latewood increased in a linear fashion and peaked in 1985 at over 66%. The proportion of latewood decreased gradually after this period and generally fluctuated between 57% and 44%, the only exception being in 1990 when latewood accounted for 37% of the annual

growth ring. The latewood proportion from 1990 to 1993 appeared to correspond to the annual growth trends. All other years appeared to be relatively independent of annual growth ring trends.

At Site PJ1971 (Figure 3-6), the growth ring measured 10.4 mm in 1973, two years after planting date. Growth increased moderately to 12.5 mm in 1974, then to 12.4 mm in 1975. After 1975 growth declined to 5.3 mm in 1977. Growth gradually slowed from this period until 1986. Growth increased in the following three years coinciding with the occurrence of a prescribed fire in 1986. Growth declined by more than 1.4 mm in 1990 and increased to 6.8 mm in 1991. Throughout the following years a number of peaks were evident in 1996, 1999 and 2001. Each of these peaks lasted no more than one year. The occurrence of multiple silvicultural treatments in 1992, 1993, 1994, 1996 and 2000 made it difficult to ascertain the influence of individual treatments. From 1996 to 2003 decreasing growth trends dominated.

Latewood in 1973 (Figure 3-6) at site PJ1971 accounted for 8% of the annual growth ring increasing in a linear fashion to 47% in 1987. After 1987 the proportion of latewood generally fluctuated between 30% and 45%, the exception being 25% in 1992. The latewood proportion from 1989 to 1992 and in 2001 appeared to correspond to the annual growth trends. All other years appeared to be relatively independent of annual growth ring trends.

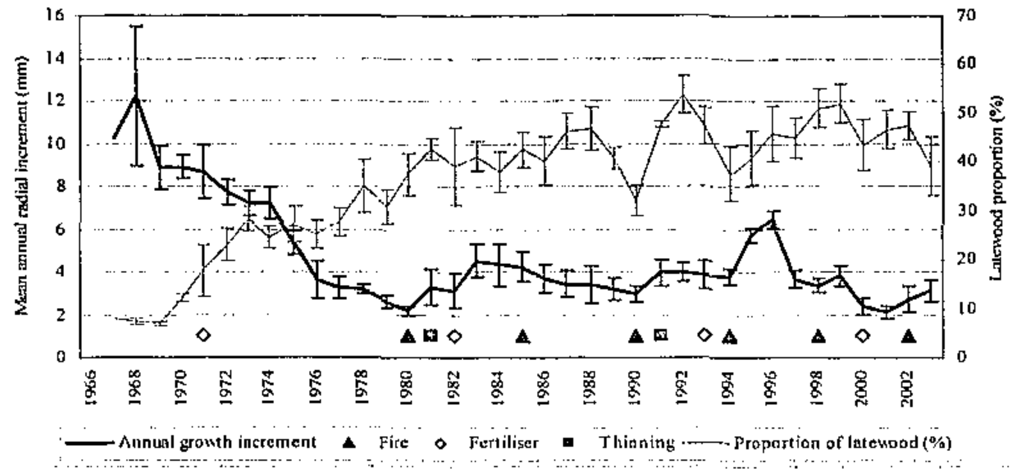

Figure 3-4: Mean and standard error time series of tree annual growth-ring increment, and proportion of latewood for chronology developed for site GN1965a. Mean refers to the arithmetic average of four measured radii of four sampled trees at each site.

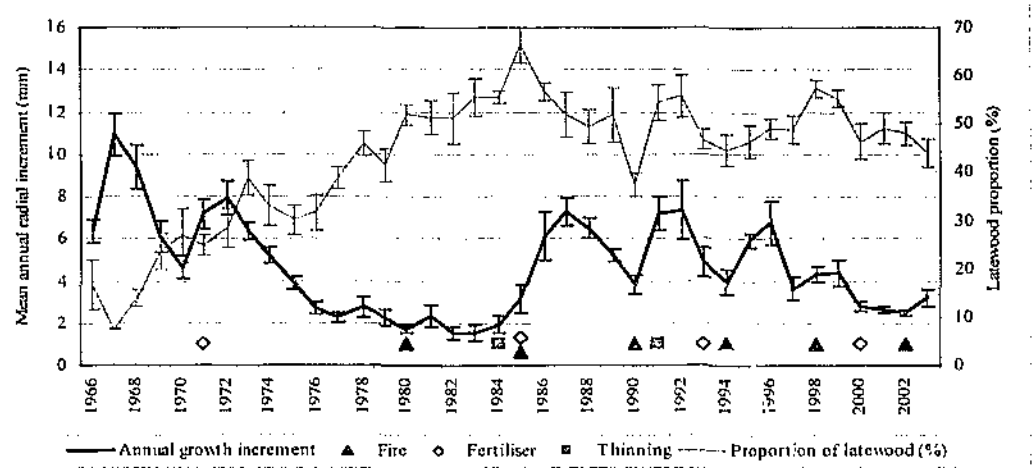

Figure 3-5: Mean and standard error time series of tree annual growth-ring increment, and proportion of latewood for chronology developed for site GN1965b. Mean refers to the arithmetic average of four measured radii of four sampled trees at each site.

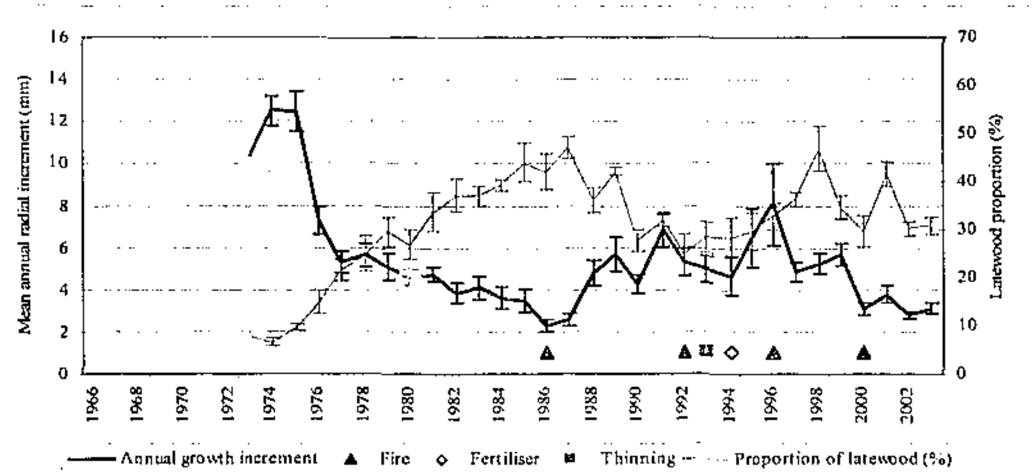

Figure 3-6: Mean and standard error time series of tree annual growth-ring increment, and proportion of latewood for chronology developed for site PJ1971. Mean refers to the arithmetic average of four measured radii of four sampled trees at each site.

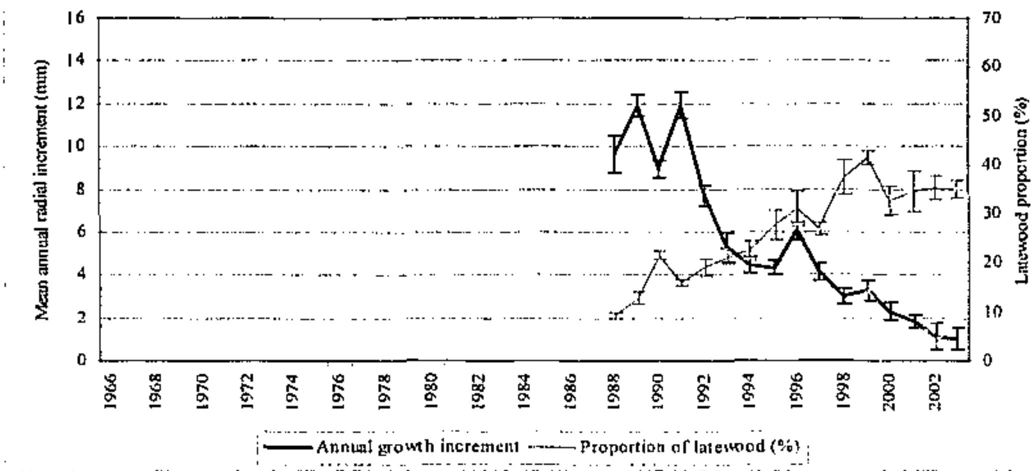

Figure 3-7: Mean and standard error time series of tree annual growth-ring increment, and proportion of latewood for developed chronology at site GN1985. Mean refers to the arithmetic average of four measured radii of four sampled trees at each site. Historically, stands GN1985 was exempt from silvicultural treatments such as prescribed fire, fertiliser application and non-commercial thinning.

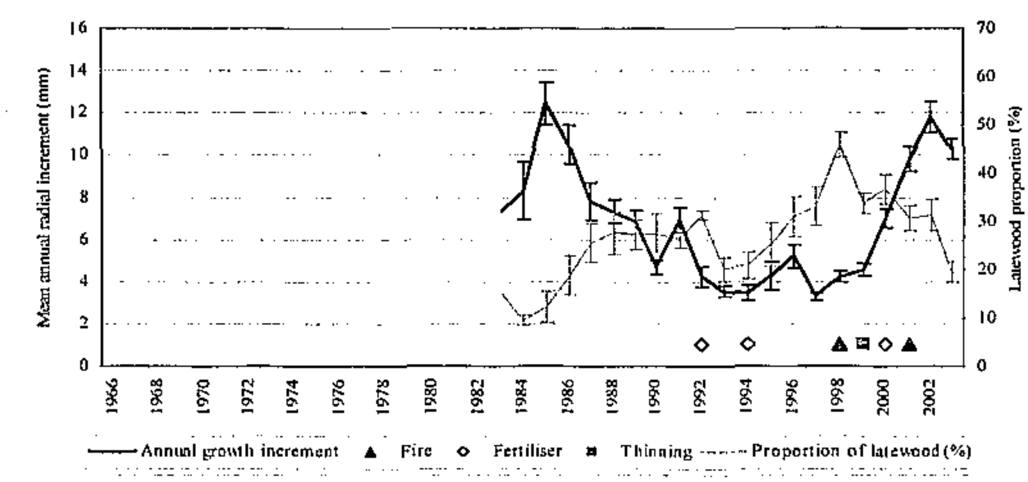

Figure 3-8: Mean and standard error time series of tree annual growth-ring increment, and proportion of latewood for developed chronology at site PJ1982. Mean refers to the arithmetic average of four measured radii of four sampled trees at each site. Historically, site PJ1982 was exempt from silvicultural treatments such as prescribed fire, fertiliser application and non-commercial thinning.

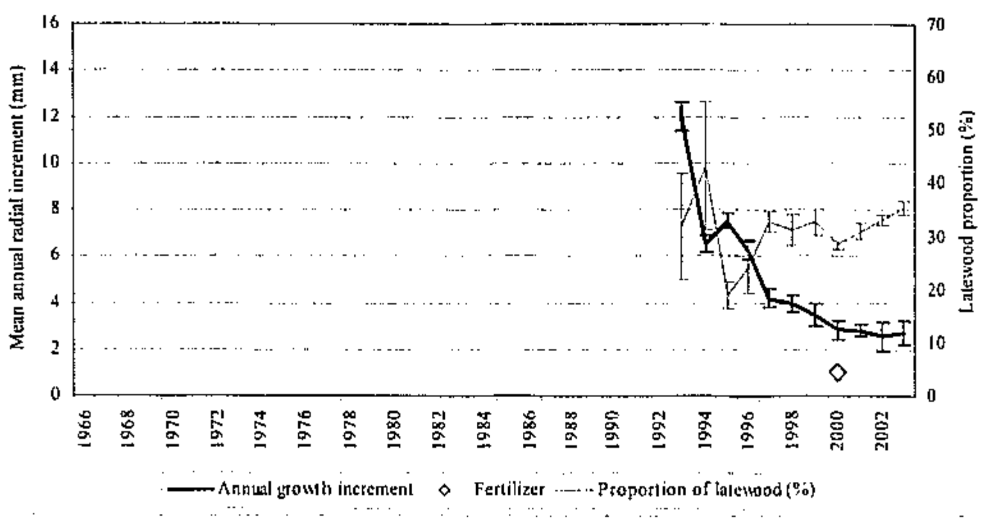

Figure 3-9: Mean and standard error time series of tree annual growth-ring increment, and proportion of latewood for developed chronology at site GN1991. Mean refers to the arithmetic average of four measured radii of four sampled trees at each site.

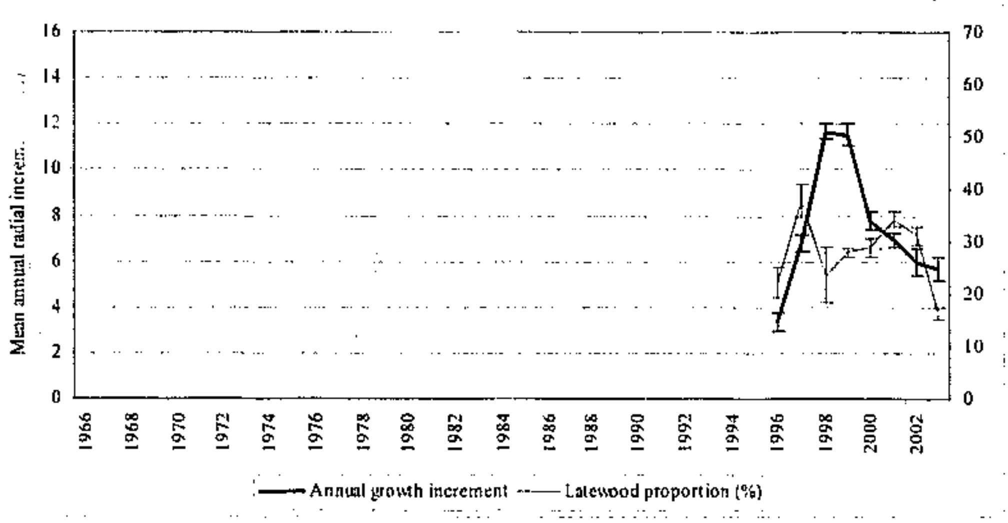

Figure 3-10: Mean and standard error time series of tree annual growth-ring increment, and proportion of latewood for developed chronology at site PJ1995. Mean refers to the arithmetic average of four measured radii of four sampled trees at each site. Historically, stands PJ1995 was exempt from silvicultural treatments such as prescribed fire, fertiliser application and non-commercial thinning.

At site GN1985 (Figure 3-7), the first distinguishable growth rings measured were from 1988, three years after planting date. Tree-ring incremental growth in 1988 was 9.6 mm, increasing to 11.9 mm in 1989. In 1990, growth decreased to 8.9 mm then increased again in 1991 to 11.9 mm in 1991. After this period growth gradually decreased over successive years, the only notable change to this trend was observed in 1996 where growth increased to 6 mm. There were no silvicultural treatments applied to site GN1985 therefore stand growth appeared to be suppressed, as indicated by declined growth trends from 1991 to 2003. The latewood proportion of annual growth was 9 mm in 1988, gradually increasing in successive years. Latewood peaked at 41% in 1999, declined to 32% in 2000 and remained relatively stable through to 2003.

At site PJ1982 (Figure 3-8) the growth ring measured 7.4 mm in 1983, one year after planting date. Growth increased to 8.3 mm in 1984, then to 12.4 mm in 1985. After 1985 growth declined rapidly to 4.7 mm in 1990. Ring size increased to 6.9mm in 1991 however decreased to 3.5 mm in 1993 and 1994. Fertilizer was applied in 1992 and 1994 but did not appear to influence ring width until after the latter treatment. Ring growth increased to 5.2 mm in 1996 then declined to 3.3 mm in 1997. In subsequent years there were a number of silvicultural treatments commencing with a prescribed fire in 1998, a thinning treatment in 1999, a fertilizer application in 2000 followed by another prescribed fire in 2001. During this period there was an increase in ring width, peaking at 11.8 mm in 2002. Growth declined slightly in 2003. Silvicultural treatments appeared to significantly influence growth trends in the last seven years of growth.

The latewood trends of site PJ1982 commenced at 15% in 1983, declined slightly in 1994 then increased in a linear fashion until 1992. Latewood decreased to 20% of the annual growth in 1993 then increased to 46% of growth in 1998. After this period the proportion of latewood decreased in a linear fashion to less than 20% in 2003.

At site GN1991 (Figure 3-9), the first two years of growth were unable to be distinguished. In 1993, two years after planting date, growth was 12 mm, decreasing to 6.5 mm in 1994. Growth increased moderately to 7.5 mm in 1995, thereafter followed by successive years of declining growth where it reached 2.7 mm in 2003. Silvicultural treatments at site GN1991 was limited to one fertilizer application in

2000 which had little influence upon growth trends. Growth of the sampled trees appeared to be suppressed, as indicated by the trends of declined incremental tree-ring growth from 1997 to 2003. The latewood proportion at site GN1991 accounted for 32% of the annual growth ring in 1993, then peaking at 43% in 1994. With the exception of 1995 the latewood proportion accounted for 28% to 35% of the annual growth ring for subsequent years.

At site PJ1995 (Figure 3-10), the growth ring measured 3.4 mm in 1996, in 1973, one year after planting date. After this period growth increment increased to 6.8 mm in 1997, then 11.7 mm in 1998 and 11.5 mm in 1999. Growth declined over subsequent years to 5.7 mm in 2003. The proportion of latewood generally fluctuated from 20% to 35%, the exception being 16% in 2003.

3.5.5 Correlation between annual tree growth-ring increment and historical climate and groundwater trends

Analysis of the annual tree growth-ring increment values revealed that there was a notable increase in growth in 1996 at five of the seven study sites (GN1985, GN1965a, GN1965b, PJ1982, and PJ1971). There were no common silvicultural treatments during this period between study sites, thus other factors such as historical climate and groundwater trends were the most likely cause of the common growth signal during 1996. The following section evaluates the influence of historical climate and groundwater trends upon annual tree growth-ring increment. A review of climate trends for each stand can be found in section 3.3.2, and groundwater trends in section 3.3.3.

As was discussed earlier, prior to statistical analysis each of the sites tree growth-ring raw measurements were averaged and transformed to dimensionless tree ring-width indices (termed standardisation) to reduce the non-climatic noise such as age related trends, and endogenous stand disturbances (Schweingruber, 1988). The dynamic response of tree growth to thinning events and other silvicultural treatments meant that in some cases the non-climatic noise remained in the derived chronologies (Woollons & Norton, 1990). The annual growth trends during the first eight to ten years growth were characteristic of the juvenile phase of stand development, therefore likely to be less responsive to rainfall trends (Hopkins, 1999a). The increased correlation with rainfall after this period can be discerned in Figure 3-11. Consequently the growth trends of the young (<15 years) and intermediate stands (15-25years) were considered to poorly represent the influence of historical water availability. With these factors in mind the influence of historical rainfall and groundwater trends upon growth were assessed using standardised chronologies developed for trees aged greater than 25 years old, each with the first ten years removed.

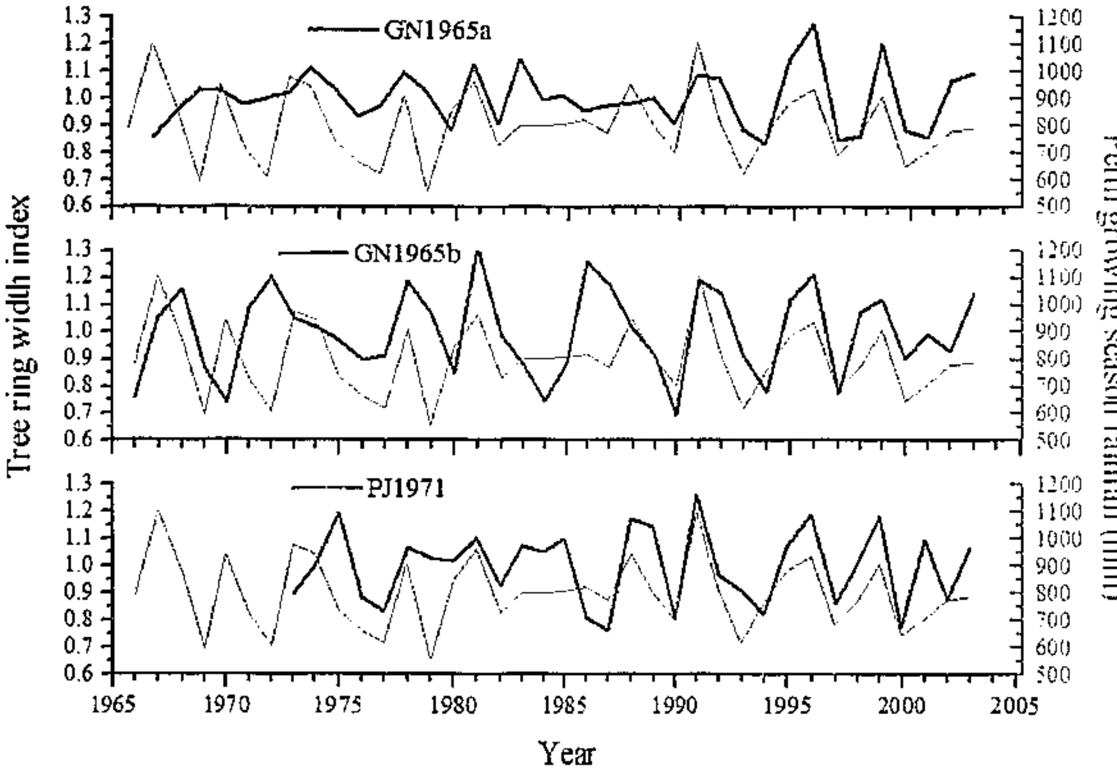

Figure 3-11: Relationship between time, Perth growing season rainfall (April to March of following year), and the mean tree ring indices for Pinus pinaster sampled from the Pinjar (PJ1971; n = 4), and Gnangara (GN1965a n=4, GN1965b; n = 4) plantations. Ring indices were computed as the robust mean value function of the detrended and standardised tree growth-ring series using a smoothing spline with a wavelength of 7 years. Standardisation of tree ring measurements was implemented to reduce non-climatic noise such as age-related trends and endogenous stand disturbances (Cook & Holmes, 1999).

Step-wise forward multiple regressions revealed that the annual growth increments for all trees aged greater than 25 years were significantly correlated to Perth's growing season cumulative rainfall (Figure 3-12). The most significant correlation between growth and rainfall was found at site PJ1971 where cumulative growth season rainfall (RT) explained 51% of the annual growth increment (F=22.06, r^2=0.51, y=0.001*RT + 0.225 p=0.000, n=23) followed by site GN1965a where growing season cumulative rainfall explained 33% of the annual growth increment (F=13.18, r^2=0.33, y=0.001*RT + 0.566 p=0.001, n=29), and then site GN1965b where growing season cumulative rainfall explained 27% of the annual growth increment (F=10.14, r^2=0.27, y=0.001*RT + 0.436 p=0.004, n=29). There was no significant relationship between the other tested environmental variables of mean, minimum and maximum and cumulative temperature, evaporation, and depth to groundwater trends.

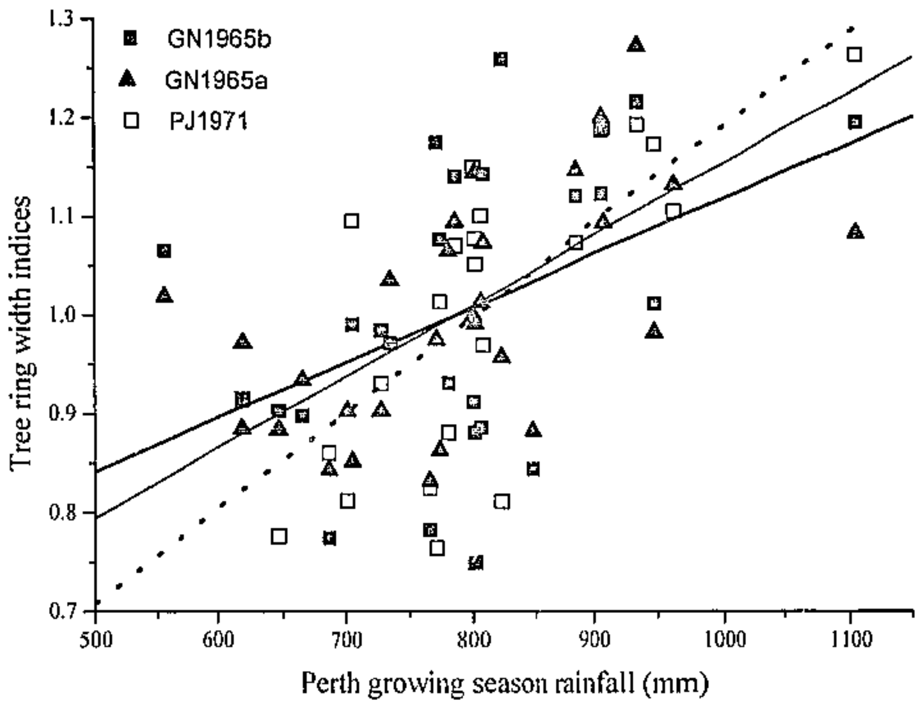

Figure 3-12: Correlation between Perth growing season cumulative rainfall (April to March of following year), and the tree ring indices with the juvenile stage removed (-10 years) for *Pinus pinaster* sampled from site GN1965a (r^2 = 0.33 p = 0.001, n = 29; black solid line), GN1965b (r^2 = 0.27 p = 0.004, n = 29; grey solid line), and PJ1971 (r^2 = 0.51 p = 0.000, n = 23; black dotted line). Ring indices were computed as the robust mean value function of the detrended and standardised tree growth-ring series using a smoothing spline with a wavelength of 7 years. Standardisation of tree ring measurements was implemented to reduce non-climatic noise such as age-related trends and endogenous stand disturbances (Cook & Holmes, 1999). The first 10 years of growth, representing the juvenile phase, was removed.

3.6 DISCUSSION

Pinus pinaster Ait. proved suitable for the development of chronologies because annual growth rings were easily distinguishable. In some cases false rings and convergent rings were observed however the use of whole-tree cross-sections facilitated the assignment of growth year. The commencement and termination of annual increments was clear, however the inner boundary of the latewood was often diffuse. Thus, although the statistical assessment of seasonality was hampered, annual resolution was appropriate to meet the studies objectives. The first two to three years of growth were indistinguishable however this was anticipated as the growth trends during this period is typically slow (Hopkins, 1999a). Trees were successfully dated and cross-dated using the dedicated software package COFECHA.

Cumulative growing season rainfall (April to March of following year) explained up to 51% of the growth trends for mature (>25 years old) stands. The contribution to radial growth due to the various combinations of mean, minimum, and maximum temperature, evaporation and depth to groundwater was statistically insignificant.

The growth trends of the Gnangara plantation study sites, representing stands with potential access to groundwater resources (<5 mbgl), and the Pinjar plantation study sites representing those without access to groundwater resources (>20 mbgl), were similar with the latter being only slightly more responsive to rainfall.

Historically it has been assumed that *Pinus pinaster* Ait. trees which are underlain by shallow groundwater resources of the superficial aquifer are directly accessing them (Butcher, 1979). Numerous studies have found that pine trees on the Gnangara Mound intercept rainfall therefore reducing recharge of the shallow aquifer (Bestow, 1971; Butcher, 1977; Farrington & Bartle, 1991; Butcher & Hopkins, 1993) but currently there is little evidence to support the theory that they are directly accessing groundwater resources. This investigation revealed that the mere presence of a shallow groundwater table does not significantly influence growth trends. Conversely rainfall and silvicultural treatments, in particular thinning treatments, were found to significantly influence the annual growth trends of *Pinus pinaster* Ait. stands occurring on the Gnangara Mound.

A growth-ring signature, characterised by a notable increase in growth was observed in five of the seven sites in 1996. The presence of this peak could not be explained by silvicultural treatments because of the heterogeneity of previous growth trends. Further assessment of the climate in 1996 revealed that the growing season rainfall (April to March of following year) in 1996 was 934 mm, only 74 mm greater than the long-term average since 1876, and 137 mm greater than the average since 1970 (Bureau of Meteorology, 2004b). Analysis of historical climate records revealed that the 1996 growing season rainfall was enhanced by 23% in June and in July, over the long-term average, corresponding to the period when the majority of height growth of *Pinus pinaster* Ait. is understood to occur (Hopkins, 1999a). The rainfall during the driest months may have also enhanced the growth. The most notable months were November, December, and March where rainfall was 129%, 58%, and 178% respectively greater than the long-term average (Bureau of Meteorology, 2004b).

The Gnangara plantation study sites are located about 30 km northeast of Perth and the Pinjar study sites about 45 km north/northwest of Perth, the distance between these sites is approximately 25 km. This study used climate data obtained from the Perth meteorological station therefore the statistical analysis did not consider stand-specific microclimate differences or climate clines. Using SILO modelled data (Queensland Department of Natural Resources and Mines, 2004), and Perth climatic data (Bureau of Meteorology, 2004b), the average rainfall of the Pinjar study sites since 1965 was estimated to be 5% less than the Perth records hence the strength of the correlation between growth and rainfall may be stronger using site-specific meteorological data (February & Stock, 1998b). As was discussed previously (section 3.3.2), data from weather stations located in closer proximity to the study sites was either incomplete, did not represent the period from 1965 to 2004 or was limited to just rainfall data rather than the required attributes such as temperature and evaporation. Furthermore, using interpolated data from the SILO data drill may also introduce error to the statistical analysis. Thus the availability of site-specific climatic data such as those from temporary weather stations would enhance future assessment of the relationship between growth trends of *Pinus pinaster* Ait. and climate.

There was no significant correlation identified between growth and groundwater trends using data collected from monitoring bores nearest to the study sites. It is

however plausible that a significant correlation between groundwater trends and growth may be identified if site-specific data were available.

The process of standardising tree growth-ring data enhanced the strength of the climate signal retained within the chronologies developed for this study (Fritts, 1976; Schweingruber, 1988; Cook, Briffa, Shiyatov, & Mazepa, 1990). This process removed much of the non-climatic signal (white noise) associated with endogenous stand disturbances, however most of the study sites were historically subjected to silvicultural treatments such as thinning, fertilizer treatments and prescribed fire, which resulted in dynamic growth trends. Consequently the standardisation process improved the signal to noise ratio, however the influence of some silvicultural treatments, thinning in particular, are likely be retained within the developed chronologies (Woollons & Norton, 1990).

The growth trends of trees sampled from Gnangara plantation sites (GN1991, GN1985, GN1965a, and GN1965b), appeared to have a consistent growth pattern over the first ten years of growth. This pattern was characterised by a linear increase in growth in the first three to five years, followed by rapid decline in growth for the following five years. These trends were relatively consistent and independent of climate, therefore most likely representing a juvenile phase of development (Hopkins, 1999a, 1999b). The growth signatures for the Pinjar plantation sites (PJ1995, PJ1982, and PJ1971) over the first ten years of growth were also observed to have a consistent trend however it differed from the Gnangara plantation sites. The presence of these differing growth characteristics may be due to the contrasting soil properties of the Bassendean Dune Complex in the Gnangara plantation sites, and the Spearwood Dune Complex of the Pinjar plantation sites (McArthur & Bettenay, 1960).

The influence of silvicultural treatments was assessed by graphically displaying the historical trends of tree-ring growth. Two of the study sites (PJ1995 and GN1985) were exempt from the silvicultural treatments of fertilizer application, thinning, and prescribed fire. Tree growth-ring increments at these sites showed a trend of suppressed growth corresponding with increased competition for resources as the stands matured (Butcher, 1977). With the exception of site GN1991, those stands where silvicultural treatments were applied were followed by a period of increased

growth, often called a release phase (Woollons & Norton, 1990). Thinning was identified as having a significant influence upon growth due to the effect of reducing competition for light, nutrients and water resources (Butcher, 1977; Alvarez Gonzalez, Schroder, Rodriguez Soalleiro, & Ruiz Gonzalez, 2002).

The two old stands (>25 years old) located in the Gnangara plantation responded differently to thinning treatments. Site GN1965a appeared to show only a marginal growth response to the thinning treatments in 1981 and 1991 (Figure 3-4). Greater increases to incremental growth were observed subsequent to the prescribed fire in 1982, the fertilizer treatment in 1982, and the prescribed fire in 1994. The greatest response observed at site GN1965a was in 1996 in response to rainfall trends (see section 3.5.5). The growth trends at site GN1965b (Figure 3-5) subsequent to silvicultural treatments were similar to those observed at site PJ1971, particularly after the thinning treatment in 1984, and the fertilizer treatment and prescribed fire in 1985.

3.6.1 Conclusion

Danjon *et al* (1999) assessed the root architecture of *Pinus pinaster* Ait. stands in France underlain by a shallow aquifer and confining layer, conditions similar to those at the Gnangara study sites. They observed that the maximum rooting depth may be approximately 20% of the stand height. There are also local unpublished studies and anecdotal support for the theory that the rooting depth of *Pinus pinaster* Ait. may extend to depths of up to 15 m below ground level, thus the pine stands located in the Gnangara study area (<5 mbgl) could theoretically have direct access to groundwater resources. However, the stands underlain by a shallow aquifer in the Gnangara plantations were most often characterised by soils with a confining hardpan. It is still not understood whether the dominant tap-root of this *Pinus* species is capable of penetrating this hardpan layer to access soil moisture available at greater depths.

If water availability (i.e. access to groundwater resources) was the factor most responsible for limiting growth then the growth trends of the sites assessed in the Gnangara plantation should have a significant correlation to groundwater trends and those located in the Pinjar plantation should not. The relationship between growth and groundwater at all sites was insignificant therefore it was not possible, using the

adopted methodology, to ascertain whether trees underlain by a shallow aquifer are directly accessing this resource.

Future investigations of groundwater use by *Pinus pinaster* Ait. on the Gnangara Mound may benefit by assessing the root architecture of the trees underlain by a hardpan layer to determine the rooting depth of the dominant tap-root.

CHAPTER 4: EVALUATION OF INTRINSIC WATER USE EFFICIENCY OF *PINUS PINASTER*: INVESTIGATION OF $\delta^{13}C$ SIGNATURE OF TREE GROWTH-RINGS AND FOLIAR MATERIAL

4.1 INTRODUCTION

Atmospheric carbon dioxide is composed of approximately 98.9% of the stable carbon isotope ^{12}C and about 1.1% of the heavier isotope ^{13}C (O'Leary, 1981). The ratio of $^{13}C/^{12}C$ is represented in parts per thousand, or per mil ‰, and can be expressed in absolute values (Δ‰), or more often is expressed relative to the Pee Dee Belemnite (PDB) standard (δ‰) (McCarroll & Loader, 2004). Analysis of the atmosphere (Keeling, Mook, & Tans, 1979; Keeling, Whorf, Wahlen, & van der Plicht, 1995), ice cores (Bert, Leavitt, & Dupouey, 1997) and tree growth rings (Francey *et al.*, 1995) has revealed that the concentration of atmospheric carbon dioxide is increasing and the proportion of these stable isotopes is changing over time. This was particularly evident from 1850 to 1950 where the proportion of ^{13}C was reduced by about 1.1‰ (Stuiver, 1978), and more recently decreased by a further 0.6‰ from 1956 to 1978 (Keeling *et al.*, 1979). In the southern hemisphere the decline appeared to stabilise from 1988 to 1990 (Francey *et al.*, 1995). These trends are tightly coupled to the emissions of CO_2 from burning ^{13}C depleted fossil fuels. Relative to the PDB standard, the atmospheric carbon dioxide composition is presently about -8‰ (Guehl *et al.*, 1995; Bert *et al.*, 1997).

^{13}C is intrinsically less reactive than ^{12}C and is discriminated against differently in C_3, C_4 and crassulacean acid metabolism (CAM) plants. The stable carbon isotopic composition of plants is therefore influenced by the physical and metabolic processes associated with photosynthesis (Farquhar, O'Leary, & Berry, 1982). In C_3 plants, diffusion of atmospheric carbon dioxide across the stomatal pathway accounts for approximately 4.4‰ of the discrimination, fractionation by the primary carboxylating enzyme, ribulose-1,5-bisphosphate carboxylase oxygenase (Rubisco) accounts for 30‰, and other processes such as respiration account for about 1‰ (O'Leary, 1981; Farquhar, Ehleringer, & Hubick, 1989). The typical discrimination range for C_3 plants is -22‰ to -34‰ (Bert *et al.*, 1997).

Stomatal conductance is influenced by solar radiation, climate, water availability and the hydraulic properties of the soil-plant-atmosphere continuum (Hubbard, Bond, & Ryan, 1999). These factors all influence ^{13}C discrimination by manipulating the relative discrimination by stomata and carboxylation (Farquhar *et al.*, 1989; Warren & Adams, 2000b). When optimal photosynthetic conditions are present discrimination against ^{13}C is the greatest (McNulty & Swank, 1995). In less favourable conditions when stomatal conductance is reduced, discrimination decreases and $\delta^{13}C$ values more closely reflect the composition of atmospheric carbon dioxide (Farquhar *et al.*, 1982; Farquhar *et al.*, 1989).

The fixation of carbon in tree growth-rings is influenced by the physical and chemical processes that occur throughout the tree. The signal embedded in these tissues will therefore represent an integrated $\delta^{13}C$ signal. This signal is retained within the relatively immobile cellulose fraction, thus the $\delta^{13}C$ signal within each growth ring represents the environmental conditions present during formation. Once the age of the tree growth-ring has been determined, correlations between the $\delta^{13}C$ signature and environmental conditions can be identified (February & Stock, 1999).

Water use efficiency (WUE) is the capacity of a plant to retain water under moisture limiting conditions, and is defined as the ratio of net photosynthesis per unit of transpiration (*A/E*) (Walcroft, Silvester, Whitehead, & Kelliher, 1997). Water use efficiency has often been determined using instantaneous gas exchange measurements, however this method has proven difficult to ascertain over longer-term trends (Valentine, 2000). $\delta^{13}C$ is linearly related to WUE (Farquhar *et al.*, 1982; Guehl *et al.*, 1995), thus the analysis of stable carbon isotopes ($\delta^{13}C$) stored in plant material has proven advantageous for the measurement of the time-integrated record of WUE (Ebdon, Petrovic, & Dawson, 1998).

Berry *et al* (1997) assessed $\delta^{13}C$ gradients in foliar material from *Pinus resinosa* in Ottawa, Canada. This study observed that foliar $\delta^{13}C$ values of the lower canopy were more negative (i.e. more depleted of ^{13}C) and they attributed this to the influence of light upon stomatal conductance. Although light was a major contributor to the $\delta^{13}C$ gradients they found that atmospheric carbon dioxide near the forest floor (<3 m) was more ^{13}C depleted, due to the recycling of respired CO_2, and may have

contributed to the $\delta^{13}C$ gradient. Francey *et al* (1985) found similar $\delta^{13}C$ trends which they attributed to light gradients as well as a juvenile phase of development where the $\delta^{13}C$ signatures of young tree growth-rings were more negative (i.e. greater ^{13}C discrimination). Evidence of an age related $\delta^{13}C$ trend in tree growth-rings is well documented in other studies (Freyer, 1979; Francey *et al.*, 1985; Panek & Waring, 1995; Porte & Loustau, 2001).

Waring and Silvester (1997) assessed the $\delta^{13}C$ signature of foliage in *Pinus radiata* in New Zealand and found that a difference of up to 6‰ was attributed to branch length and aspect. Increased $\delta^{13}C$ values were observed in longer branches located on the north-western aspect (side with greatest sun exposure) of the canopy. This indicated that stomatal conductance and hydraulic conductance had greater influences upon $\delta^{13}C$ than height. Warren and Adams (2000b) also found a significant relationship between branch length and $\delta^{13}C$ in *Pinus pinaster* Ait, particularly at a site located in a low rainfall region in Wickepin, Western Australia.

Schleser (1992) assessed the influence of foliar $\delta^{13}C$ gradients associated with canopy position upon $\delta^{13}C$ values in leaves, twigs and stem material. This study identified that a $\delta^{13}C$ gradient observed in foliar material was not evident in stem material. Leavitt and Long (1986) conducted a similar study of pinyon pine in New Mexico and also found no significant correlation between the foliar $\delta^{13}C$ gradients and tree growth-ring $\delta^{13}C$ values.

The principles of ^{13}C discrimination in C_3 plants has been used extensively to assess the historical climate and water availability (Francey & Farquhar, 1982; Farquhar & Richards, 1984; Leavitt & Long, 1986). Walcroft *et al* (1997) analysed $\delta^{13}C$ from whole-tree cross-sections removed from two *Pinus radiata* plantations of differing water availability (rainfall and soil moisture) in New Zealand. The $\delta^{13}C$ discrimination was greatest (most negative) at the wettest site, therefore agreeing with the model outlined by Farquhar *et al* (1989). Warren *et al* (2001) analysed $\delta^{13}C$ from stem-wood and foliage from *Pinus pinaster* and *Pinus radiata* in Western Australia. Contrary to expectations, low density stands (250s/ha^{-1}) were found to be more water use efficient than dense stands (750s/ha^{-1}), highlighting the significance

of other factors influencing stomatal conductance and enzyme activity such as irradiance and nutrient availability.

The application of carbon isotope theory in controlled laboratory environments has been successful in determining interspecies and intra-species $\delta^{13}C$ trends (Farquhar *et al.*, 1989). In the natural environment the influences upon photosynthesis change over time and space. Therefore the transfer of these principles into observational studies has proven more difficult (Bert *et al.*, 1997; February & Stock, 1999; Valentine, 2000). In light of the demonstrated relationship between water availability and the $\delta^{13}C$ signature, this study aimed to evaluate the influence of historical climate and groundwater trends upon the water use efficiency of *Pinus pinaster* Ait. stands occurring on two divergent groundwater regimes. This study was designed to address the hypothesis that there is no significant difference in water use efficiency between trees which potentially have access to shallow groundwater resources (<5 mbgl) and those which do not (>20 mbgl), the inference being that *Pinus pinaster* Ait. stands do not directly access groundwater resources of the superficial aquifer of the Gnangara Mound. Specific objectives were as follows:

i. To evaluate the correlation between intrinsic water use efficiency and historical growth trends of *Pinus pinaster* Ait.

ii. To evaluate the influence of historical climate upon intrinsic water use efficiency of *Pinus pinaster* Ait.

iii. To evaluate the influence of shallow groundwater resources (<5 mbgl) upon intrinsic water use efficiency of *Pinus pinaster* Ait. by comparing them with stands underlain by deep groundwater resources (>20 mbgl).

4.2 MATERIALS AND METHODS

Twenty eight trees were destructively sampled for the assessment of interannual $\delta^{13}C$ stored in tree growth-rings and foliar material. Site selection and sampling methodology is described in Chapter 2. Historical climate, groundwater trends, silvicultural treatments, and the methodology for the development of tree ring chronologies are detailed in Chapter 3.

4.2.1 Fundamental assumptions pertaining to $\delta^{13}C$ discrimination measurements

Recycling of ^{13}C depleted atmospheric CO_2 can occur near the forest floor due to recycling of CO_2 from root, soil and plant respiration (Berry *et al.*, 1997). The study sites lack an understorey stratum and the air surrounding the sampled foliage is relatively well mixed, therefore recycling of ^{13}C depleted CO_2 is assumed to be negligible. The composition of the atmospheric carbon dioxide is assumed to have remained at about -8‰ since the oldest sampled trees were established in 1965 thus changes in $\delta^{13}C$ are attributed to the physiological responses of individual trees to historical environmental conditions such as light interception, climate and groundwater trends.

4.2.1.1 Foliar sampling

Pinus pinaster Ait. is monocyclic typically producing one flush of growth per year. However they are known to develop more than one growth flush in the leader shoot (Hopkins, 1999b). The leaves are also relatively persistent and are known to be retained for five years on average (Warren & Adams, 2000b). Leaf elongation commences in August and is mostly complete by March of the following year (Warren & Adams, 2000a). With this in mind it is anticipated that the leaf samples collected in April for the purpose of this study represents a full 12 months of growth, therefore the $\delta^{13}C$ signature corresponds to the environmental conditions of the previous growing season.

In addition to $\delta^{13}C$ analysis, foliar nitrogen concentrations were assessed. The fertilizer treatments throughout the Gnangara and Pinjar plantations are limited to the application of phosphorus based products (unpublished data from the Forest Products Commission), therefore nitrogen levels within foliar material may remain relatively unchanged over time. The benefit of assessing foliar nitrogen concentration is that it can be used as a proxy for soil nutrient levels present at study sites.

At each sample site three foliar samples were removed from the northern aspect of each tree representing the lower, middle and upper strata. For each stratum the branch length was measured from the growing tip to the main stem and the vertical height from this point to the ground. This parameter was recorded to test the relationship between canopy position, branch length and $\delta^{13}C$. Total pathway length was calculated as a sum of branch length plus branch height.

Annual leaf whorls were separated and labelled with a C denoting the 2003 growing season, C+1 for the previous year through to C+6 representing the 1997 growing season (Warren & Adams, 2000b). In most cases annual leaf whorls were easily discernable by a bud scar though when not obvious, leaf whorls were still considered to be two separate years. The $\delta^{13}C$ results were reviewed to determine whether these samples represented one or two years of growth.

Each leaf whorl (n=327) was oven dried for three weeks at 60^0C. Dry needles were pooled, cut into smaller sections then placed into 2 ml vials. Samples were then pulverized with a Retsch MM200 ball mill using two 6.3 mm stainless steel ball-bearings. Finely ground samples were weighed (5.9-6.1 mg) and placed in 6 x 4 mm tin-foil capsules for $\delta^{13}C$ analysis.

4.2.1.2 Tree growth-ring sampling

The $\delta^{13}C$ values of tree growth-rings are often radially variable (Leavitt & Long, 1986), however the relative difference between tree growth-rings along an axis remains similar (Mazany, Lerman, & Long, 1980). Consequently from each stem cross-section a 2 mm thick tangential section from the northern azimuth was removed with a drop-saw, then oven dried to a constant mass at 60^0C. Annual growth

rings were then carefully separated on the basis of distinct colour changes denoting earlywood and latewood, thus each $\delta^{13}C$ sample represented an average value for the growing season. Wood samples (n=629) were processed as per the foliar samples described above.

4.2.1.3 Cellulose extraction

Fractionation of ^{13}C is influenced by the number of biochemical reactions, the greater the number of reactions the greater the ^{13}C discrimination (Macfarlane, Warren, White, & Adams, 1999). Whole-wood contains various proportions of materials such as cellulose, hemicellulose, and lignin, each comprising of a different $\delta^{13}C$ signal. Unlike many other wood components cellulose is relatively immobile therefore it is the preferred material for $\delta^{13}C$ analysis (Green, 1963; Stuiver, 1978; Leavitt & Danzer, 1993; Bert *et al.*, 1997; Loader, Robertson, Barker, Switsur, & Waterhouse, 1997; Macfarlane *et al.*, 1999). The process of cellulose extraction is relatively time consuming, consequently a preliminary trial was undertaken to determine the correlation between the $\delta^{13}C$ signature of whole-wood and cellulose. If a significant correlation exists ($p < 0.05$) then all further assessment of $\delta^{13}C$ could be performed on whole-wood only, therefore reducing the need for the additional step.

Many methods are available for cellulose extraction including the Jayme-Wise method (Green, 1963), the Brendel method (Brendel, Iannetta, & Stewart, 2000), and the modified diglyme-HCl method (Macfarlane *et al.*, 1999). The latter procedure produces crude cellulose which retains a portion of lignin (-0.3‰ bias) however it can be performed quickly, is relatively simple, and does not require specialised glassware. Changes to the methods outlined in Macfarlane *et al* (1999) are detailed below.

4.2.1.3.1 Di-glyme HCL methodology

Fifty pulverised wood samples from tree growth-rings from the Gnangara (GN1965a, n=15: GN1965b, n=15) and Pinjar sites (PJ1971, n = 15: PJ1982, n=5) were selected for cellulose extraction. These samples represented periods of contrasting growth and rainfall. For each sample approximately 50 mg of pulverised wood was passed

through a 600 μm sieve and placed into a 20 ml glass vial with 4.5 ml of di-glyme (99% diethylene glycol dimethyl ether) and 0.5 ml of 10M HCl. Each vial was crimped closed with an aluminium seal with teflon-butyl liners and placed into a pre-heated shaking water bath at 90^0C. After 1hr the seal was removed and the contents filtered through pre-weighed and labelled filter paper (70 mm cellulose) which was folded into a cone shape and fitted to 50 ml funnels inserted into a 100 ml conical flask. The brown coloured residue was washed with 20 ml of methanol, and 50 ml of boiling DI water. The filter papers were oven dried overnight at 60^0C and weighed to determine the yield as a proportion of initial weight. Care was taken not to contaminate the sample with cellulose fibres from the filter paper. Three wood samples returned insufficient material for $\delta^{13}C$ analysis, therefore a total of 47 samples were analysed.

4.2.1.4 $\delta^{13}C$ analysis

Stem and foliar $\delta^{13}C$ were determined by combusting samples to CO_2 in the presence of O_2 (Europa Scientific, ANCA-GSL, Crewe, UK) before passing into a continuous flow isotope ratio mass spectrometer (Europa Scientific, 20-20, Crewe, UK). $\delta^{13}C$ was calculated relative to the PDB standard using a laboratory flour standard ($\delta^{13}C$ = 40.37%C, δPD4 -25.34‰; $\delta^{15}N$ = 1.67%N, 3.01‰; Europa Scientific). $\delta^{13}C$ values were expressed in parts per mil (‰) using the equation:

$$\delta^{13}C\ (‰) = (R_{sample} / R_{standard} - 1) \times 1000$$

During $\delta^{13}C$ analysis, leaf samples were also analysed for nitrogen concentration and $\delta^{15}N$. Nitrogen levels in tree growth-ring samples were below laboratory detectible limits and therefore not assessed. The nitrogen foliar $\delta^{15}N$ and nitrogen concentrations are detailed in Appendix 17-20.

4.3 Data analysis

Historical $\delta^{13}C$ trends for the four sampled sites in the Gnangara plantation and three sites in the Pinjar plantation were analysed by graphically displaying the mean

annual $\delta^{13}C$ trends over time. Pearsons Moment correlation was used to compare $\delta^{13}C$ of whole-wood and $\delta^{13}C$ in crude cellulose.

Step-wise forward multiple linear regressions were performed to evaluate the influence of the mean, minimum, maximum, and cumulative rainfall, temperature, evaporation and groundwater levels upon interannual $\delta^{13}C$ signatures of tree growth-rings of all age classes. The first ten years growth representing an identified juvenile phase (see Chapter 3) was removed in initial statistical analyses and was found to make no significant difference to the strength of identified correlations. Correlations between $\delta^{13}C$ values in tree growth-rings and incremental growth were assessed using raw ring width measurements because the processes of producing tree ring width indices (termed standardisation, refer to Chapter 3) removes age related growth trends. The analysis of foliar $\delta^{13}C$ was used to assess the correlation between the branch length, branch height and total pathway length of the current year's foliar $\delta^{13}C$, and the mean $\delta^{13}C$ of all persistent foliage.

All data were analysed using routines contained within the statistical packages Origin (V5.0) and SPSS (V11.5).

4.4 RESULTS

4.4.1 Comparison between δ13C signature of whole-wood and crude cellulose

A significant correlation between the $\delta^{13}C$ signature of whole-wood and crude cellulose (f=219.2, r^2 = 0.83, Y = 2.268 + 1.0691 * X p<0.0001) was obtained with crude cellulose being on average 0.60‰ (±0.05) less negative than whole-wood (Figure 4-1). This result is consistent with other studies (Macfarlane *et al.*, 1999; Warren *et al.*, 2001) therefore reliable isotopic data can be obtained from whole-wood. Warren and Adams (2000b) also identified a similar trend in foliar material, consequently all subsequent analysis of $\delta^{13}C$ was derived from whole-wood and leaf samples.

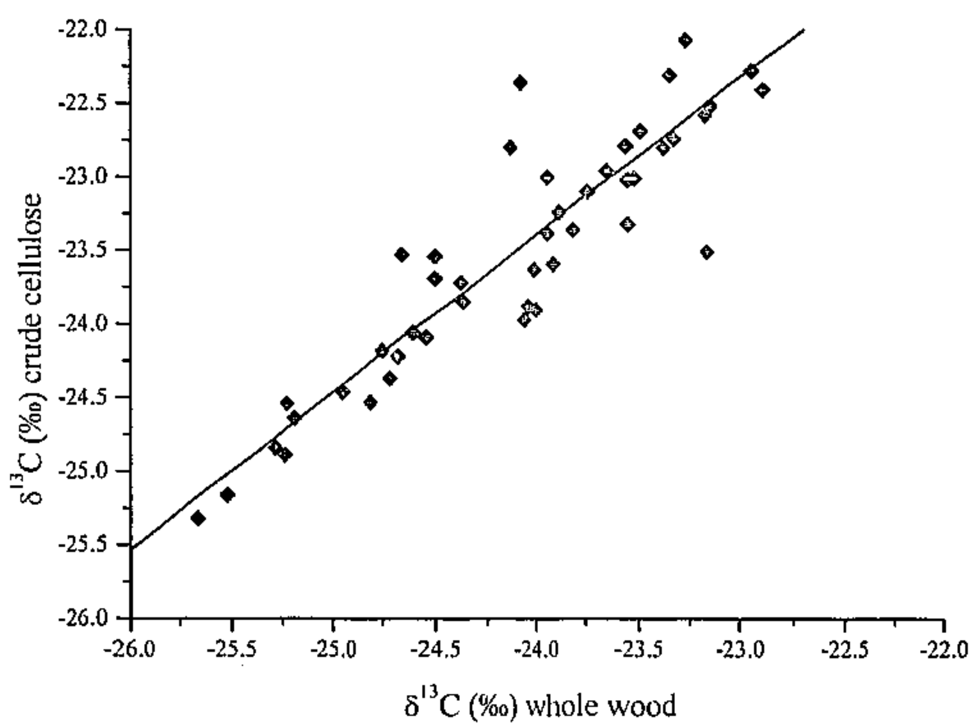

Figure 4-1: Relationship (including line of best fit) between $\delta^{13}C$ of whole-wood versus $\delta^{13}C$ of crude cellulose extracted from *Pinus pinaster* Ait. tree growth-rings (n = 47). Points represent growth rings from dry and wet periods from the Gnangara plantation (n = 27) and the Pinjar plantation (n = 20). A significant correlation (f=219.2, r^2 = 0.83, Y = 2.268 + 1.0691 * X p<0.0001) existed between whole-wood and crude cellulose, the latter on average was 0.60‰ less depleted of ^{13}C. Crude cellulose was extracted using the modified di-glyme method (Macfarlane *et al.*, 1999).

4.4.2 Analysis of interannual $\delta^{13}C$ signature of tree growth-rings

Analysis of foliar $\delta^{13}C$ and nitrogen concentrations revealed no significant differences between sites for each canopy position. Branch length, branch height, and total pathway length (sum of branch length and branch height) in all cases are significantly correlated to $\delta^{13}C$ values ($P<0.05$). This indicates that a number of factors in addition to climate, such as light interception and hydraulic conductivity are significantly influencing the $\delta^{13}C$ values (Panek & Waring, 1995; Panek, 1996; Warren & Adams, 2000b). With this in mind foliar $\delta^{13}C$ did not enhance the evaluation of the correlation between the stable carbon isotope signatures of tree growth-rings and historical climate, and groundwater trends. A detailed review of foliar nitrogen characteristics are given in Appendix 29.

4.4.2.1 Correlation between $\delta^{13}C$ of tree growth-rings and annual radial growth increment

Statistical analysis revealed that the annual tree growth-ring width measurements at site GN1985, PJ1982 and PJ1971 were significantly correlated ($P<0.05$) to tree growth-ring $\delta^{13}C$ explaining 44%, 22% and 19% of the $\delta^{13}C$ values respectively (Table 4-1). The correlations at these sites indicated that more positive $\delta^{13}C$ values are related to increased annual tree growth-ring increments (Figure 4-2).

Table 4-1: Correlations between the mean tree growth-ring $\delta^{13}C$ and mean tree growth-ring annual growth increment measurements. ^{S} denotes that correlations are significant at P<0.05.

Site ID	Equation	df	r^2 value	p	F	A	B
GN1965a	Y = A*x + B	37	0.01	0.58	0.31	-24.69	0.02
GN1965b	Y = A*x + B	36	0.09	0.07	3.43	-24.22	-0.06
PJ1971	Y = A*x + B	31	0.19	0.013^{S}	6.95	-24.74	0.10
GN1985	Y = A*x + B	16	0.44	0.005^{S}	10.91	-25.86	0.12
PJ1982	Y = A*x + B	21	0.21	0.037^{S}	5.05	-24.97	0.09
GN1991	Y = A*x + B	11	0.04	0.54	0.41	-25.75	0.03
PJ1995	Y = A*x + B	8	0.32	0.15	2.78	-25.06	0.08

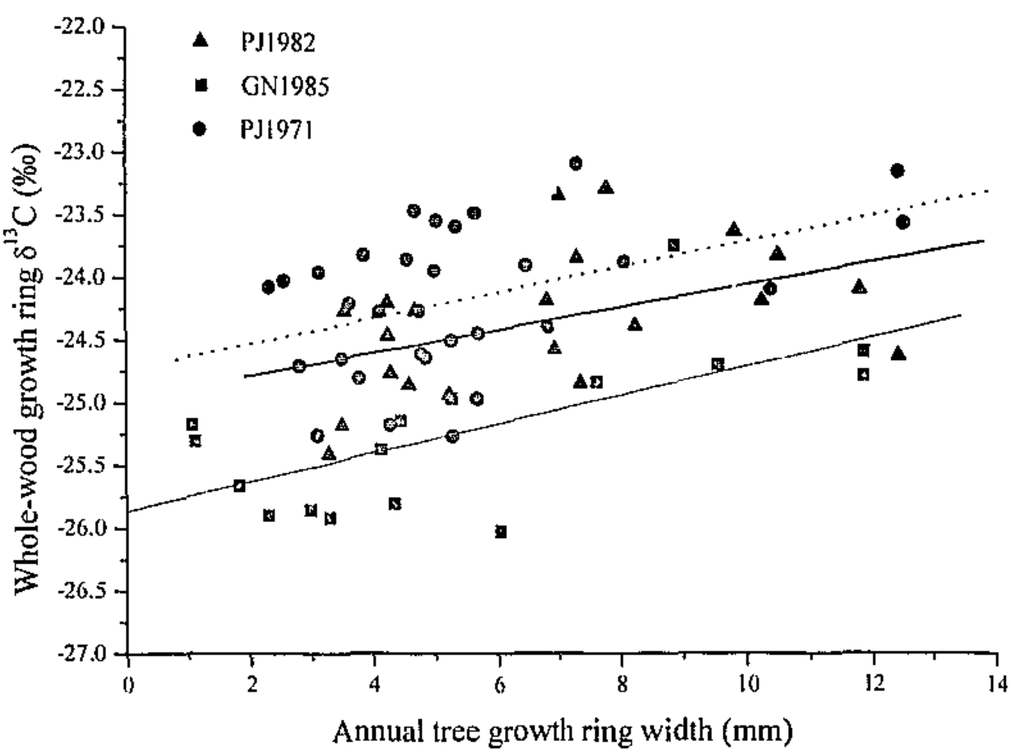

Figure 4-2: Relationship between mean whole-wood $\delta^{13}C$ and the mean annual tree growth ring width measurements for *Pinus pinaster* Ait. sampled from site GN1985 (r^2 = 0.44 p = 0.005, n = 16; grey solid line), PJ1982 (r^2 = 0.21 p = 0.037, n = 21; black solid line), and PJ1971 (r^2 = 0.19 p = 0.013, n = 31; black dotted line).

4.4.2.2 Annual $\delta^{13}C$ of tree growth-rings and the influence of silvicultural treatments

Subsequent to statistical analysis the average annual $\delta^{13}C$ values of the tree growth-rings from each site were graphically illustrated and subjectively compared. This was undertaken to evaluate the influence of silvicultural treatments on $\delta^{13}C$ values.

At site GN1965a the mean $\delta^{13}C$ was equal to the mean for all sites. Commencing in 1967, two years after planting date, the $\delta^{13}C$ value was -25.64‰ (Figure 4-3). In subsequent years $\delta^{13}C$ increased (becoming less negative) in a linear fashion to -23.48‰ in 1972 and decreased to -24.65‰ in 1973. After 1973, $\delta^{13}C$ gradually increased to -23.82‰ in 1982, however a moderate fall was evident in 1977, followed by a moderate peak in 1978. Between 1983 and 1993 there were a series of peaks and troughs, the most notable was observed between 1983 and 1989 where each peak was followed a trough of approximately 0.5‰. In 1993 $\delta^{13}C$ gradually decreased from -24.02‰ to -25.13‰ in 2003. The relationship between $\delta^{13}C$ and annual incremental growth was difficult to delineate. Silvicultural treatments appeared to influence the $\delta^{13}C$ signature, for example relatively minor increases in $\delta^{13}C$ were observed subsequent to a fertilizer treatment in 1971, thinning treatments in 1981 and 1991, and the prescribed fire in 1985. There was no statistically significant correlation between the $\delta^{13}C$ signature and the corresponding annual tree growth-ring increment measurement (f=0.31, $r^2 < 0.01$, P=0.58).

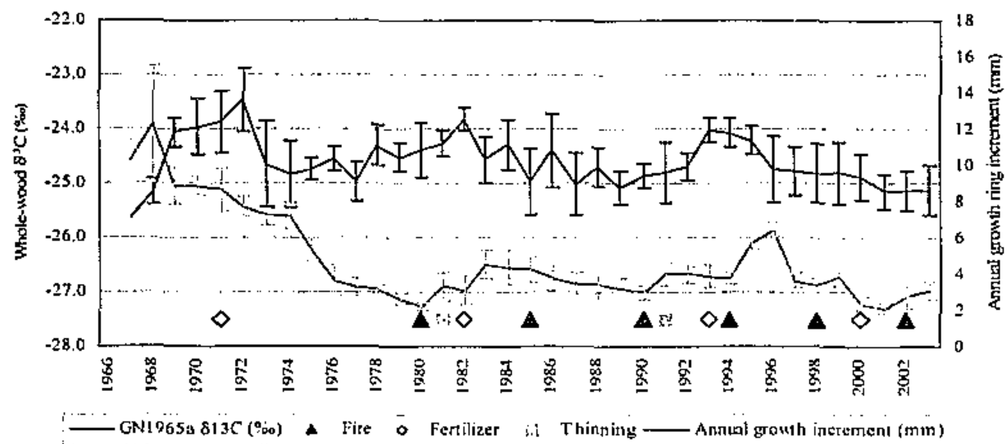

Figure 4-3: Mean and standard error time series of the interannual δ^{13}C signature of tree growth-rings, and the mean annual growth-ring increment and standard error for site GN1965a. The mean annual increment refers to the arithmetic average of four measured radii of four sampled trees.

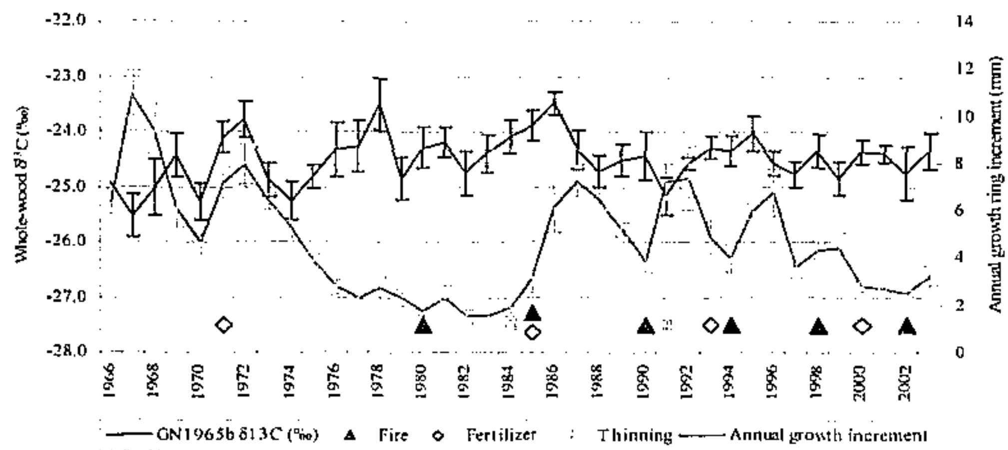

Figure 4-4: Mean and standard error time series of the interannual δ^{13}C signature of tree growth-rings, and the mean annual growth-ring increment and standard error for site GN1965b. The mean annual increment refers to the arithmetic average of four measured radii of four sampled trees.

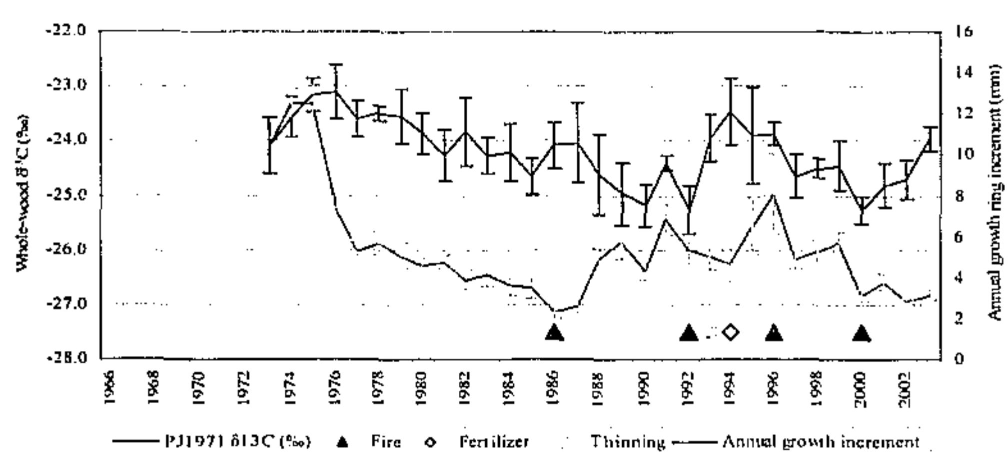

Figure 4-5: Mean and standard error time series of the interannual δ^{13}C signature of tree growth-rings, and the mean annual growth-ring increment and standard error for site PJ1971. The mean annual increment refers to the arithmetic average of four measured radii of four sampled trees.

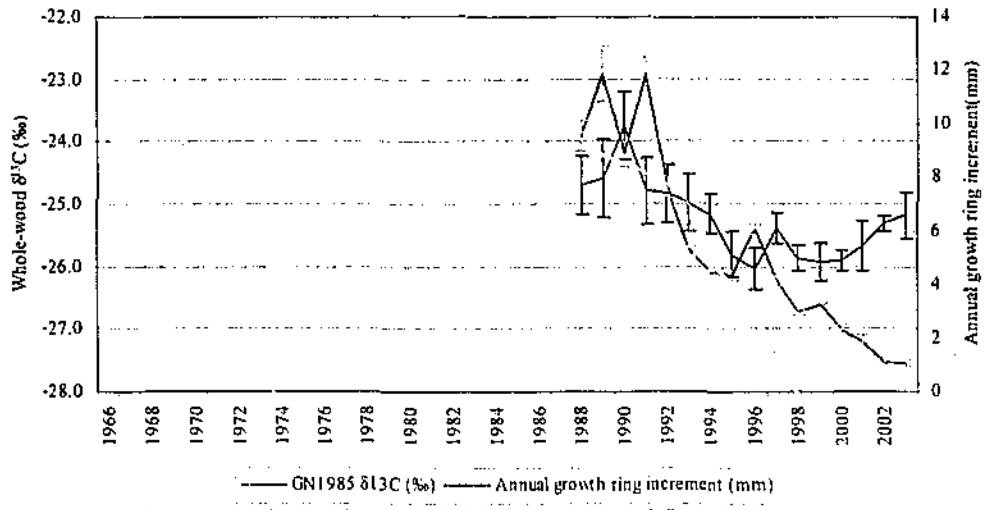

Figure 4-6: Mean and standard error time series of the interannual $\delta^{13}C$ signature of tree growth-rings, and the mean annual growth-ring increment and standard error for site GN1985. The mean annual increment refers to the arithmetic average of four measured radii of four sampled trees.

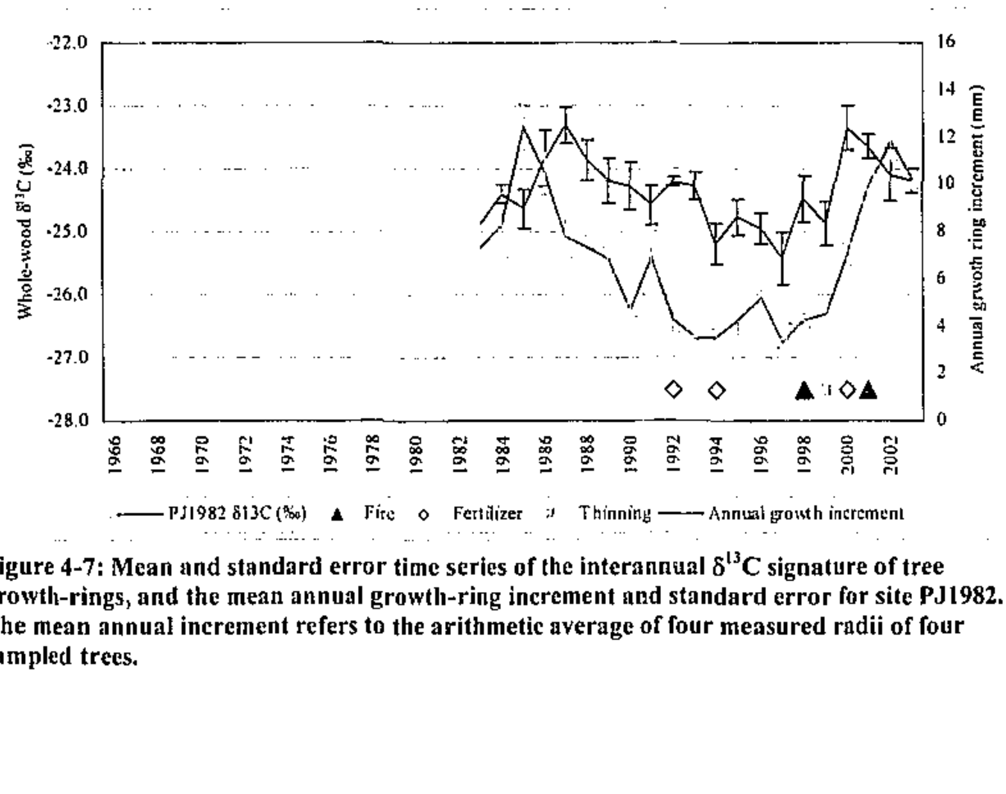

Figure 4-7: Mean and standard error time series of the interannual $\delta^{13}C$ signature of tree growth-rings, and the mean annual growth-ring increment and standard error for site PJ1982. The mean annual increment refers to the arithmetic average of four measured radii of four sampled trees.

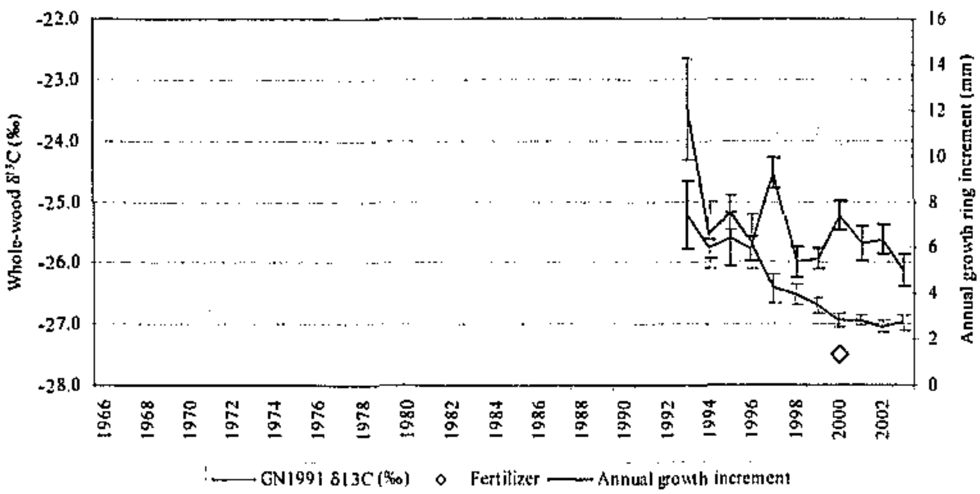

Figure 4-8: Mean and standard error time series of the interannual $\delta^{13}C$ signature of tree growth-rings, and the mean annual growth-ring increment and standard error for site GN1991. The mean annual increment refers to the arithmetic average of four measured radii of four sampled trees.

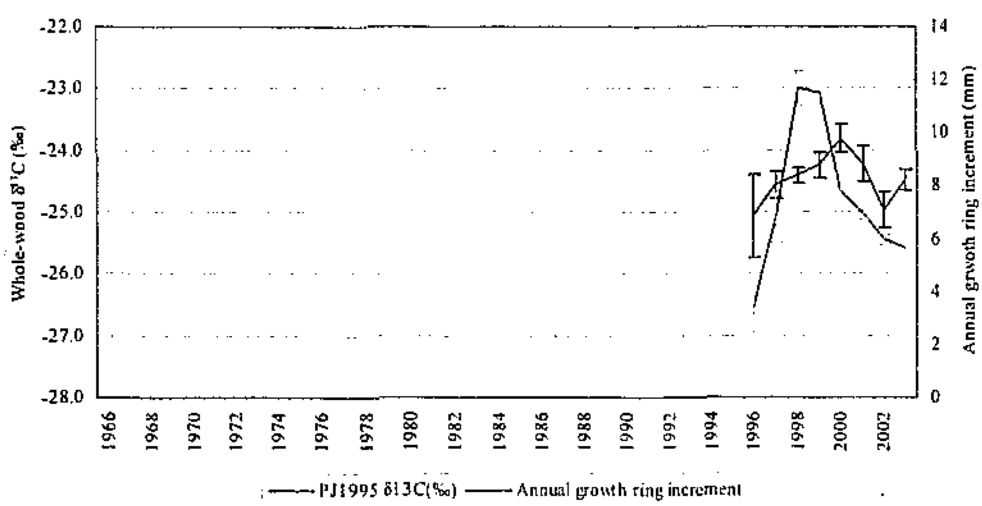

Figure 4-9: Mean and standard error time series of the interannual $\delta^{13}C$ signature of tree growth-rings, and the mean annual growth-ring increment and standard error for site PJ1995. The mean annual increment refers to the arithmetic average of four measured radii of four sampled trees.

At site GN1965b (Figure 4-4) the mean $\delta^{13}C$ was marginally greater than the mean for all sites (0.09‰). In 1966 (one year after planting), the $\delta^{13}C$ signature was recorded for one tree and was -24.91‰ (Figure 4-4). From 1967 to 1972, $\delta^{13}C$ generally increased in a linear fashion (less negative) from -25.52‰ to -23.79‰, the exception being -25.26‰ in 1970. $\delta^{13}C$ decreased to -24.88‰ in 1973, then to -25.25‰ in 1974. From 1974 to 1978 $\delta^{13}C$ increased in a linear fashion to -23.51‰ then decreased to -24.85‰ in 1979. In 1980 and 1981 $\delta^{13}C$ increased slightly by approximately 0.5‰ then decreased to -24.75 in 1982. After 1982 $\delta^{13}C$ again increased in a linear fashion to a peak of -23.49‰ in 1986. Between 1987 and 2003 $\delta^{13}C$ generally fluctuated between -24.0‰ and -25.5‰.

There were no consistent correlations between $\delta^{13}C$ and growth trends at site GN1965b. Some years such as 1972, 1978, 1981 and 1986 the $\delta^{13}C$ signature appeared to correlate with growth trends, these particular years were characterised by $\delta^{13}C$ increasing relative to increasing growth trends. An increase in $\delta^{13}C$ in 1971 and 1972 coincided with a fertilizer application in 1971. The effects of subsequent fertilizer treatments were difficult to determine, particularly as they frequently coincided with other treatments. This was also the case for prescribed burning. The effects of thinning upon $\delta^{13}C$ in 1984 were similar to those at site PJ1982 (Figure 4-7) and GN1965a (Figure 4-3) with $\delta^{13}C$ increasing following the treatment. Interestingly the thinning treatment in 1991 corresponded with a moderate $\delta^{13}C$ decrease. The $\delta^{13}C$ trend following the thinning treatment in 1991 is opposite to that occurring at site GN1965a (Figure 4-3). There was no statistically significant correlation between the $\delta^{13}C$ signature and the corresponding annual tree growth-ring increment measurement (f=3.43, r^2=0.09, P=0.072).

At site PJ1971 (Figure 4-5), the mean $\delta^{13}C$ was greater (less negative) by 0.4‰ than the mean for all sites. Commencing at 1973 (two years after planting) the $\delta^{13}C$ value was -24.10‰ and increased in a linear fashion to -23.10‰ in 1976. From 1976 to 1992 the $\delta^{13}C$ value steadily decreased to -25.27‰, the exceptions to this pattern were observed in 1982 (-23.83‰), 1986 (-24.08‰), 1987 (-24.03‰), 1988 (-24.61‰) and 1991 (-24.40‰). In 1993 the $\delta^{13}C$ increased to -23.95‰ then to -23.47‰ in 1994. After this period $\delta^{13}C$ decreased in a linear fashion to -25.26‰ in 2000, with a moderate increase observed in 1999 (-24.45‰). After 2000, $\delta^{13}C$

increased in successive years to -23.96‰ in 2003. The influence of prescribed burning and fertilizer treatments upon $\delta^{13}C$ was difficult to delineate however there was a rapid $\delta^{13}C$ increase subsequent to the thinning treatment in 1993. There was a significant relationship between $\delta^{13}C$ and annual tree growth-ring increment (f=6.95, r^2=0.19, P=0.013) at site PJ1971.

At site GN1985 (Figure 4-6), the average $\delta^{13}C$ value was -25.24‰ (+/-0.16), therefore ~0.3‰ less negative than the average. In 1988 (three years after planting date), the $\delta^{13}C$ value was -24.70‰ and increased to -23.75‰ in 1990. $\delta^{13}C$ decreased to -24.79‰ in 1991 and continued to decrease by less than 0.2‰ per year until 1996 then increased to -25.38‰ in 1997. From 1998 to 2000 $\delta^{13}C$ averaged approximately -25.9‰ then gradually increased in subsequent years to -25.18‰ in 2003. There was a significant relationship between $\delta^{13}C$ and annual tree growth-ring increment (f=10.91, r^2=0.44, P=0.005) at site GN1985. This trend was most apparent after 1998 where an increase to $\delta^{13}C$ correlated with successive years of decreased annual tree ring growth.

At site PJ1982 (Figure 4-7), the average $\delta^{13}C$ was 0.2‰ less negative than the mean at -24.35‰ (±0.12). Commencing from 1983 (one year after planting date) the $\delta^{13}C$ value was -24.85‰ and generally increased in a linear fashion to -23.30‰ in 1987. After 1987 $\delta^{13}C$ decreased from -23.85‰ in 1988 to -24.58‰ in 1991. $\delta^{13}C$ increased to approximately -24.2‰ in 1992 and 1993 then decreased to -25.18‰ in 1994. $\delta^{13}C$ increased to -24.77‰ in 1995 then decreased slightly to -24.94‰ in 1996 and -24.41‰ in 1997. In subsequent years the $\delta^{13}C$ value increased, peaking at -23.35‰ in 2000 and decreased to -24.19‰ in 2003. $\delta^{13}C$ increases were observed during periods of increased incremental growth. This trend was particularly evident after the thinning treatment in 1999. It was difficult to ascertain the influence of other silvicultural treatments. A significant correlation was identified, with annual tree growth-ring increment explaining 21% of $\delta^{13}C$ variation (f=5.05, r^2=0.21, P=0.037).

At site GN1991 (Figure 4-8) the $\delta^{13}C$ trends of the first five to six years were similar to those at site GN1965b (Figure 4-4). The average $\delta^{13}C$ value was -25.59‰ (+/-0.14) which was equal to the average for all sampled sites. Commencing in 1993 (two years after the planting date) the $\delta^{13}C$ value was -25.24‰ then decreased to -25.78‰ in 1994. The $\delta^{13}C$ signature remained relatively constant over the next two years until 1997 where it increased to -24.53‰. $\delta^{13}C$ decreased to approximately -25.9‰ for the next two years then increased to -25.53‰ in 2000. After 2000 a declining $\delta^{13}C$ trend appeared to predominate reaching a $\delta^{13}C$ value of -26.12‰ in 2003. There was no significant correlation between the $\delta^{13}C$ signature and the corresponding annual tree growth-ring increment measurement (f=0.40, r^2 =0.04, P=0.54).

At site PJ1995 (Figure 4-9) the $\delta^{13}C$ trends of the first five to six years were similar to site PJ1971 (Figure 4-5). The average $\delta^{13}C$ value was approximately 1‰ less negative than the average at -24.47‰ (+/-0.14). In 1996 (one year after planting date) the $\delta^{13}C$ value was -25.07‰. $\delta^{13}C$ increased in a linear fashion (less negative) over the next four years, reaching a peak in 2000 at -23.82‰. After 2000 $\delta^{13}C$ declined to -24.96‰ in 2002 and increased to -24.48‰ in 2003. There was no significant correlation between the $\delta^{13}C$ signature and the corresponding annual tree growth-ring increment measurement (f=2.77, r^2=0.32, P=0.147).

4.4.2.3 Correlation between $\delta^{13}C$ of tree growth-rings and historical climate, and groundwater trends.

There were no consistent correlations between $\delta^{13}C$ and historical climate or groundwater trends. Significant correlations ($P<0.05$) between tree growth-ring $\delta^{13}C$ values, historical climate and/or groundwater trends were identified at only four sites, being GN1965a, GN1965b, PJ1971 and GN1985 (Table 4-2).

Table 4-2: Results of step-wise linear regression relationships between mean tree growth-ring $\delta^{13}C$ and historical climate and groundwater trends. At site GN1965b two variables were found to significantly correlate to $\delta^{13}C$, these were mean annual maximum depth to groundwater and Perth's growing season cumulative rainfall consequently three correlations representing the three combinations are detailed below.

Site ID	Equation	df	r^2 value	p	F	A	B_1	B_2
GN1965a	$Y = A + B * a$	37	0.42	0.001	14.39	-22.41	-0.650	-
GN1965b	$Y = A + (B_1 *a) + (B_2*b)$	36	0.26	0.005	6.23	-24.22	0.187	-0.001
PJ1971	$Y = A + B * c$	31	0.16	0.035	4.94	-20.10	-0.165	-
GN1985	$Y = A + B *$ d	16	0.53	0.001	15.66	-22.07	-0.002	-

Model used

a. Predictor: mean annual maximum depth to groundwater (nearest bores)

b. Predictor: Perth's growing season total rainfall

c. Predictor: mean annual depth to groundwater (nearest bores)

d. Predictor: Perth's growing season cumulative evaporation

At site GN1965a the average maximum depth to groundwater, at bores GN22 and NR6C, was significantly related ($P<0.05$) to the $\delta^{13}C$ signature of tree growth-rings explaining 42% of the $\delta^{13}C$ trends (Table 4-2). A negative relationship was identified between depth to groundwater and $\delta^{13}C$, indicating that as the depth to groundwater decreased (i.e. became close to the surface) the $\delta^{13}C$ values became more positive (Figure 4-10).

At site GN1965b a significant ($P<0.05$) positive correlation was observed (i.e. as depth to groundwater increased $\delta^{13}C$ became less negative) between the mean maximum depth to groundwater, at bores L200A and WM32 and $\delta^{13}C$ however this only explained 14% of the $\delta^{13}C$ trends. This trend was the opposite of what occurred at site GN1965a (Figure 4-11). Forward stepwise regressions also revealed that growing season cumulative rainfall explained 14% of the $\delta^{13}C$ trends. The two factors were statistically analysed together (Table 4-2) and explained 26% of the

$\delta^{13}C$ trends although the groundwater trends of the shallow superficial aquifer are closely related to rainfall events (Davidson, 1995) therefore a collinear relationship may exist between the assessed parameters.

At site PJ1971 a significant negative ($P<0.05$) correlation was observed (i.e. as depth to groundwater increased $\delta^{13}C$ became more negative) between $\delta^{13}C$ and the annual mean depth to groundwater, at bores P320 and P310 (Table 4-2). The line graph revealed that the correlation although statistically significant is difficult to validate, particularly since the annual mean groundwater trends explains only 16% of the $\delta^{13}C$ (Figure 4-12).

A significant relationship ($P<0.05$) was found between $\delta^{13}C$ at site GN1985 and the growing season cumulative annual evaporation (Table 4-2). The correlation over time was plotted on a line graph (Figure 4-13) to assist with the assessment of the relationship between these parameters. A negative relationship indicated that as evaporation increased the $\delta^{13}C$ value became more negative.

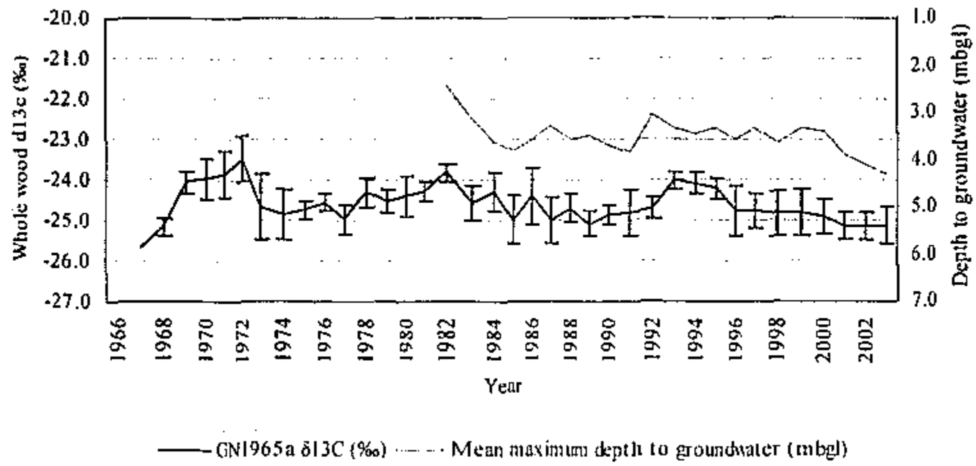

Figure 4-10:Mean and standard error time series of the intrinsic $\delta^{13}C$ signature analysed from tree growth-rings from the northern aspect of four trees sampled from site GN1965a and the mean maximum depth to groundwater derived from data collected from bores GN22 and NR6C (Department of Environment, 2004).

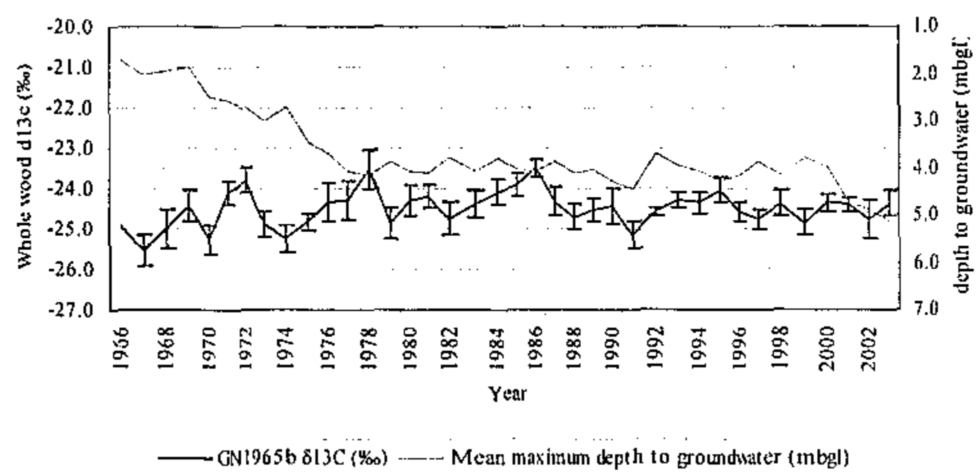

Figure 4-11: Mean and standard error time series of the intrinsic $\delta^{13}C$ signature analysed from tree growth-rings from the northern aspect of four trees sampled from site GN1965b and the mean maximum depth to groundwater derived from data collected from bores L200A and WM32 (Department of Environment, 2004).

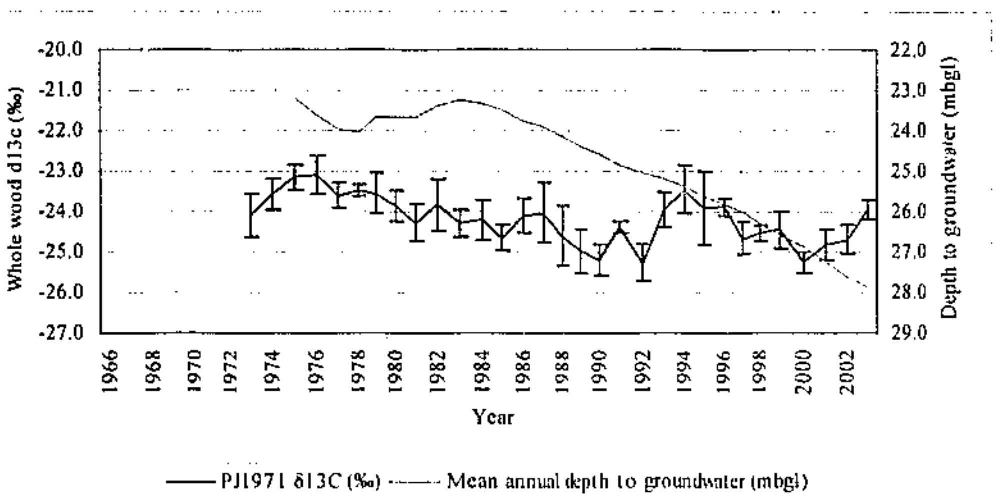

Figure 4-12: Mean and standard error time series of the intrinsic $\delta^{13}C$ signature analysed from tree growth-rings from the northern aspect of four trees sampled from site PJ1971 and the mean annual depth to groundwater derived from data collected from bores P320 and P310 (Department of Environment, 2004).

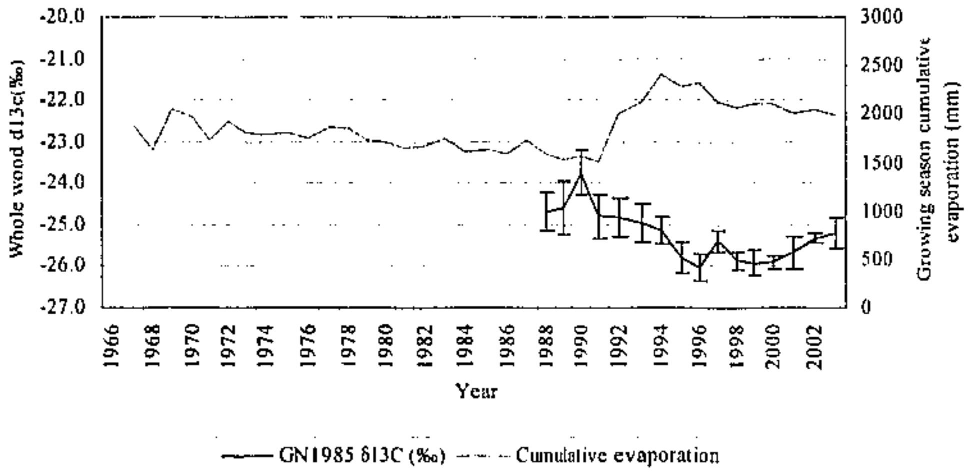

Figure 4-13: Mean and standard error time series of the intrinsic $\delta^{13}C$ signature analysed from tree growth-rings from the northern aspect of four trees sampled from site GN1985 and the growing season (April to March) cumulative evaporation recorded at the Perth weather station (Bureau of Meteorology, 2004b).

4.5 DISCUSSION

4.5.1 The applicability of $\delta^{13}C$ to determine water use efficiency in *Pinus pinaster* Ait.

The study design was implemented to identify, where practical, the various factors influencing $\delta^{13}C$ values of foliar and tree growth-ring material prior to evaluating the relationship between $\delta^{13}C$ and water use efficiency of *Pinus pinaster* Ait. stands occurring on two contrasting groundwater regimes.

The influence of $\delta^{13}C$ variability associated with the mobilisation of plant materials such as lignin, hemicellulose and waxes was evaluated during a preliminary analysis of the $\delta^{13}C$ signature of whole-wood and crude cellulose. Using the modified di-glyme method outlined by Macfarlane *et al* (1999) this study found a significant and predictive relationship ($P<0.05$) between the $\delta^{13}C$ signature of whole-wood and crude cellulose with the latter being about 0.60‰ less negative. These results indicated that reliable isotopic data could be obtained from $\delta^{13}C$ analysis of whole-wood (Macfarlane *et al.*, 1999) consequently all subsequent analysis of $\delta^{13}C$ were derived from whole-wood and leaf samples.

In some species the nutritional status of soils may influence the carbon dioxide assimilation to transpiration rate (*A*/*E*), therefore influencing the $\delta^{13}C$ signal (Guehl *et al.*, 1995; Brooks *et al.*, 1997). Warren *et al* (2001) found that thinning treatments of *Pinus pinaster* and *Pinus radiata* increased soil nutrient availability resulting in increases to foliar nitrogen of 0.2% to 0.3% respectively, therefore potentially contributing to $\delta^{13}C$ values. The nitrogen concentrations analysed from foliar samples in this study (see Appendix 17-20) indicated that the soil nutrient conditions at the Gnangara and Pinjar plantation sites were similar and therefore unlikely to contribute to differences between foliar and tree growth-ring $\delta^{13}C$ values. A cautionary note must be made about this assumption because Teskey and Sheriff (1996), in a study of 16 year old *Pinus radiata* in South Australia, found that different fertilizer treatments were not reflected in foliar material. Therefore to adequately account for the influence of nutrients upon $\delta^{13}C$ it is recommended that future studies assess soil nutrients.

The influence of canopy position upon foliar $\delta^{13}C$ values was evaluated by sampling from the lower, middle and upper strata of each tree. The foliage $\delta^{13}C$ signatures revealed the presence of discrimination gradients with the lower strata at most sites being most negative (see Appendix 29). These results conformed with other similar studies (Berry *et al.*, 1997; Brooks *et al.*, 1997; Waring & Silvester, 1997). All foliage was sampled from the northern aspect of each tree therefore the $\delta^{13}C$ gradient was most likely attributed to light gradients whereby the upper leaves were intercepting more light leading to reduced stomatal conductance (Farquhar *et al.*, 1982).

The influence of hydraulic conductivity upon $\delta^{13}C$ discrimination was tested using a basic measurement of branch length, branch height and total pathway length (sum of branch length and branch height) (Warren & Adams, 2000b). These factors were all significantly correlated to foliage $\delta^{13}C$ values and could explain up to 26% of the $\delta^{13}C$ value (Appendix 29). The use of branch length parameters as a proxy for hydraulic conductivity is a simple model which does not take into account the complex water transport processes throughout the entire tree neither does it take into consideration the soil-plant-atmosphere continuum (Hubbard *et al.*, 1999) however it did provide a useful proxy to identify the influence of hydraulic conductivity upon stomatal conductance and ^{13}C discrimination.

Hydraulic conductivity and light gradients were found to significantly influence $\delta^{13}C$ values, and foliar material represented a $\delta^{13}C$ signal for a maximum of five years, therefore considered unsuitable for the evaluation of the influence of historical climate and groundwater trends upon water use efficiency.

4.5.1.1 Correlation between $\delta^{13}C$ of tree growth-rings and annual radial growth increment

The $\delta^{13}C$ signatures of tree growth-rings sampled from Gnangara plantation sites (GN1991, GN1985, GN1965a, and GN1965b), regardless of age class, appeared to have a consistent pattern over the first five or six years of growth. The $\delta^{13}C$ signatures for the Pinjar plantation sites (PJ1995, PJ1982, and PJ1971) also had a consistent trend however it differed from the Gnangara plantation sites. This may

represent the juvenile stage of development and different trends may be due to contrasting soil properties of the Bassendean Dune Complex in the Gnangara plantation sites, and the Spearwood Dune Complex of the Pinjar plantation sites. However there did not appear to be any evidence of the juvenile phase described in other studies, whereby the plant material become more enriched with ^{13}C over time (Francey *et al.*, 1985; Panek & Waring, 1995; Porte & Loustau, 2001).

Results from this study identified a significant correlation ($P<0.05$) between $\delta^{13}C$ and annual tree growth-ring increment at three sites, being GN1985, PJ1982 and PJ1971, explaining 44%, 21% and 19% of $\delta^{13}C$ values respectively.

Site GN1985 is an intermediate aged stand (15-25 years) located in the Gnangara plantation, and is underlain by shallow groundwater resources (<5 mbgl) (Figure 4-6). This site was exempt from silvicultural treatments consequently the annual incremental growth trends and $\delta^{13}C$ trends reflected the process of stand maturation where competition for water or nutrient resources increases over time (Francey *et al.*, 1985). Subjective analysis of the line plot (Figure 4-13) indicates that the positive $\delta^{13}C$ values in the first five or six years of growth were indicative of a juvenile phase of development. $\delta^{13}C$ trends after this period were negatively related to growth where positive incremental growth peaks correlated to more negative $\delta^{13}C$ values. The statistical model based upon the general trends indicates the opposite trend where positive $\delta^{13}C$ trends are associated with positive incremental growth trends. This highlights the difficulties with assessing $\delta^{13}C$ trends from relatively young trees.

Light was unlikely to be the primary cause of increased $\delta^{13}C$ values at site GN1985, particularly after 1998, because as a stand approaches canopy closure, light interception decreases leading to increased stomatal conductance (Waring & Silvester, 1997), thus $\delta^{13}C$ would become more negative. From the observed trends $\delta^{13}C$ values in tree growth-rings at site GN1985 represent historical trends in water availability therefore providing a useful indicator of intrinsic water use efficiency.

Site PJ1982 is an intermediate aged stand (15-25 years) without access to groundwater resources (>20 mbgl), located in the Pinjar plantation. The $\delta^{13}C$ trends were positively related to annual tree growth-ring increment (i.e. more positive $\delta^{13}C$

values associated with periods of increased growth). These trends indicate that increased incremental growth trends occurred during periods of decreased water or nutrient resource availability, or periods of increased light interception. The most positive $\delta^{13}C$ values were observed after the thinning event in 1999 therefore the $\delta^{13}C$ values appear to represent historical light interception trends. With these points in mind, the $\delta^{13}C$ signature assessed from site PJ1982 is not a useful indicator of intrinsic water use efficiency.

Site PJ1971 is an old stand (>25 years), without access to groundwater resources (>20 mbgl) and is located in the Pinjar plantation. As with site PJ1982, positive $\delta^{13}C$ values were associated with increased annual incremental growth. Prior to the thinning event in 1993 (Figure 4-5), $\delta^{13}C$ trends were generally declining indicating that either water or nutrient resources were becoming increasingly available or the canopy was reaching closure and light incidence was decreasing. After the thinning event in 1993, $\delta^{13}C$ increased rapidly indicating that the increased $\delta^{13}C$ was a stomatal response to increasing light interception (Warren *et al.*, 2001). With this in mind, $\delta^{13}C$ did not provide a useful indicator of intrinsic water use efficiency.

4.5.1.2 Correlation between $\delta^{13}C$ of tree growth-rings and historical climate, and groundwater trends.

The link between historical climate and groundwater trends upon $\delta^{13}C$ was found to be statistically ($P<0.05$) significant at four sites GN1985, GN1965a, GN1965b and PJ1971. There were however no consistent correlations. The $\delta^{13}C$ values interestingly revealed contrasting $\delta^{13}C$ trends at sites GN1965a and GN1965b. These stands were planted at the same period, with a similar stand structure, and similar historical silvicultural treatments. Consequently $\delta^{13}C$ signatures of tree growth-rings were not an effective indicator of intrinsic water availability without consideration of other site specific characteristics. The sites where significant correlations between $\delta^{13}C$, and historical climate and groundwater trends are detailed below.

The strongest relationship was identified at site GN1985 (Figure 4-13) where the growing season cumulative evaporation explained 53% of the $\delta^{13}C$ signature in tree growth-rings. Evaporation is an integrated measure of temperature and humidity. A

negative correlation was found indicating that as evaporation increased the $\delta^{13}C$ value became more negative. These results were contrary to the anticipated trends because the carbon isotope model suggests that as evaporation increases the stomata reduce conductance to reduce water loss (Farquhar *et al.*, 1989). Subjective analysis of the data further supported the statistical model however this correlation is difficult to interpret, particularly since this relationship was not identified at any other stand. Further investigation is therefore required to identify unique stand or microclimate characteristics. The results of this particular analysis highlight the limitations of evaluating such relationships at relatively large spatial and temporal resolutions.

At site GN1965a, maximum annual depth to groundwater trends explained 42% of the $\delta^{13}C$ trends of tree growth-rings. The observed relationship indicates that a decreasing $\delta^{13}C$ signature over time corresponded to declining groundwater levels (Figure 4-10). If the sampled trees were utilising groundwater resources then opposite $\delta^{13}C$ trend would have occurred whereby $\delta^{13}C$ values would increase as groundwater levels declined, becoming more water use efficient. The hypothesis for the $\delta^{13}C$ trends at site GN1965a is that historically during periods of shallow groundwater levels, waterlogging of the rhizosphere may have occurred leading to root induced stomatal closure (Dubos & Plomion, 2003). In April, 2004 the site soil assessment undertaken for this study indicated that the capillary fringe was about 2.5 metres below ground level and that a mottled soil horizon was present below 1.6 m, graduating to a hard calcrete layer with a sulphurous odour (Appendix 24). These conditions are indicative of a soil profile subject to seasonal flooding or waterlogging (Plaster, 1997), therefore supporting the hypothesis that waterlogging of the soil profile may increase $\delta^{13}C$ values, thus increasing water use efficiency. The trends observed at site GN1965a mean that $\delta^{13}C$ may not be a useful indicator of intrinsic water use efficiency without further investigation into the interaction between a shallow groundwater table and the root architecture of the trees on this site.

At site GN1965b $\delta^{13}C$ was significantly correlated ($P<0.05$) with maximum depth to groundwater (Figure 4-11). Contrary to the trends observed at site GN1965a, $\delta^{13}C$ increased as maximum groundwater levels declined (i.e. as groundwater levels declined the sampled trees became more water use efficient). The $\delta^{13}C$ trends infer that the sampled trees are directly influenced by shallow groundwater resources. Although the correlation is significant, maximum depth to groundwater trends can

only explain 14% of the $\delta^{13}C$ value. Cumulative growing season rainfall was also significantly ($P<0.05$) correlated with $\delta^{13}C$, and explained 14% of the variation of $\delta^{13}C$. Together, maximum depth to groundwater and cumulative growing season rainfall explained 26% of the $\delta^{13}C$ variation (Table 4-2). The close relationship between groundwater trends of the superficial aquifer and rainfall, particularly in shallow soil profiles (Davidson, 1995), makes it difficult to delineate whether the sampled trees are directly accessing groundwater or are intercepting soil water recharged from rainfall. Alternative methods for determining water source partitioning such as the measurement of pre-dawn and midday xylem pressure potential, instantaneous water use efficiency, and the measurement of $\delta^{18}O$ and $\delta^{2}H$ in plant material, groundwater and soil, are therefore recommended.

At site PJ1971 a significant negative correlation ($P<0.05$) between $\delta^{13}C$ and the annual mean depth to groundwater was observed, explaining 16% of the $\delta^{13}C$ trends. Subjective analysis of the correlation between these parameters (Figure 4-12) revealed that although both variables were declining over time, the correlation appeared incidental. The mean groundwater trends between 1975 and 1983 appeared to fluctuate however after this period declined in a linear fashion. $\delta^{13}C$ trends are best described as being dynamic and appear to be responding to an environmental factor other than groundwater trends. With this in mind, $\delta^{13}C$ did not provide a useful indicator of intrinsic water use efficiency.

4.5.2 Conclusion

The key finding of this research was that $\delta^{13}C$ failed to exhibit consistent correlations with historical climate and groundwater trends. Silvicultural treatments in many cases appeared to have the greatest influence upon $\delta^{13}C$. Thus the diversity of silvicultural treatments made the comparison between $\delta^{13}C$ values of sampled trees from the Gnangara and Pinjar sites complex. The hypothesis that there is no significant difference in water use efficiency between trees which potentially have access to shallow groundwater resources (<5 mbgl) and those which do not (>20 mbgl) was unable to be validated due to the complexity of factors other than water availability influencing $\delta^{13}C$. Given the nature of current forest management practices on the Gnangara Mound, $\delta^{13}C$ may not be suitable for determining intrinsic water use efficiency of *Pinus pinaster* Ait. stands.

CHAPTER 5: SYNTHESIS

Analysis of growth rings revealed that growth trends of *Pinus pinaster* Ait. occurring on the Gnangara Mound, regardless of the underlying groundwater conditions, are significantly influenced by silvicultural treatments and cumulative growing season rainfall (April to March of the following year). The trees sampled from the Pinjar plantation do not have access to groundwater resources (>20 mbgl) and appear more responsive to rainfall than the trees from the Gnangara plantation, which have access to groundwater resources (<5 mbgl). The difference between the growth trends in response to rainfall however was insignificant, therefore growth trends did not reveal whether those trees underlain by a shallow groundwater table directly access this resource.

Analysis of stable carbon isotopes in tree growth-rings revealed no consistent correlations between $\delta^{13}C$ and historical climate, or groundwater trends therefore $\delta^{13}C$ was not an appropriate indicator of historical water availability. A significant correlation between $\delta^{13}C$ and growth trends was evident at only three study sites. Thus this study reiterates the difficulties associated with the application of $\delta^{13}C$ analysis in natural environments (Bert *et al.*, 1997; February & Stock, 1999).

5.1.1 Growth trends and the significance of silvicultural treatments and rainfall

Pinus pinaster Ait. proved suitable for chronology development because earlywood and latewood rings were easily delineated and analysis revealed that growth patterns are strongly influenced by environmental change (Stokes & Smiley, 1968). The commencement and termination of annual increments was clear, however the inner boundary of the latewood was often diffuse. Thus the statistical assessment of seasonality was hampered, however annual resolution was appropriate to meet the study's objectives. The use of whole-tree cross-sections made the delineation of annual growth-rings relatively straightforward.

An investigation of the soil properties of the study sites revealed the presence of contrasting soil types. The soils of the Pinjar plantation sites are indicative of the Spearwood Dune Complex with deep yellow sands throughout the profile (McArthur & Bettenay, 1960). The Gnangara sites are typical of poorly drained areas of the Bassendean Complex, and are characterised by white/grey sands in the upper profile underlain by mottled sands and a humus or calcrete hardpan at ~2.5m. (McArthur & Bettenay, 1960). At one of the Gnangara plantation sites (GN1965b) the soil profile differed as the mottled horizon is absent and is characterised by dry white/grey sands terminating at a brown hardpan at 2.8m. The presence of a mottled soil horizon is indicative of a soil profile subject to seasonal flooding or waterlogging (Plaster, 1997), thus different growth trends observed between these two sites may be attributed to the different soil characteristics of the Bassendean Dune Complex.

By sampling three age classes this study was able to isolate the influence of age upon growth trends from other factors such as climate and genetic progeny. The first ten years of growth was identified as a juvenile stage of development, whereby consistent growth patterns emerged irrespective of the climate and groundwater trends (Hopkins, 1999a, 1999b). The Gnangara plantation study sites and the Pinjar sites each appeared to have their own unique growth characteristics during this phase. The contrasting soil properties of the Gnangara and Pinjar plantations is most likely the primary influence upon these trends.

Assessment of the historical growth trends indicated that after the juvenile phase of development, growth declined with age. This trend was due to the physiological process of aging (Fritts, 1967), and the increased competition for water, nutrient and light resources as the stand matured (Butcher, 1977). Those stands where silvicultural treatments were applied were often followed by a period of increased growth, often called a release phase (Woollons & Norton, 1990). Thinning in particular was identified as the treatment most significantly influencing growth due to the effect of reducing competition for light, nutrients and water resources (Butcher, 1977; Alvarez Gonzalez *et al.*, 2002).

Historically it has been assumed that *Pinus pinaster* Ait. trees which are underlain by shallow groundwater resources of the superficial aquifer of the Gnangara Mound,

are directly accessing them (Butcher, 1979). If this were the case then the strength of the climate signal, represented as growth responses to climate, would be stronger in the trees which did not have access to groundwater resources. Analysis of growth trends was unable to support this assumption because this hypothesis fails to consider the diversity of factors influencing water availability such as silvicultural treatments and site-specific conditions.

The limitations of this hypothesis were highlighted upon review of the growth trends at the two old sites (>25 years old) in the Gnangara plantation (site GN1965a, and GN1965b). These two stands are located approximately 1.5km from each other, were planted at the same time, and had a similar history of silvicultural treatments. Site GN1965a showed moderate growth responses to thinning treatments, and responded better to prescribed fire and fertilizer treatments. The growth responses to silvicultural treatments at site GN1965b were similar to those observed at the Pinjar plantation sites, with large ring-width increases following thinning treatments, and moderate increases observed after prescribed fire and fertilizer application. Thus it was apparent that the mere presence of a shallow groundwater table could not account for growth responses to silvicultural treatments.

One of the key principles of dendrochronology is the use of signature growth-rings to identify the year of formation, and to then cross-reference these signature rings between developed chronologies (Fritts, 1976; Schweingruber, 1988). Signature rings are those which are formed during years of exceptionally low or high resource availability, or years for example where the cambium is damaged as a consequence of a fire event (Burrows, Ward, & Robinson, 1995). A common growth increase occurred in 1996 at five of the seven sites, irrespective of historical silvicultural treatments. The rainfall during the 1996 growing season period (April 1996 to March 1997) was only marginally greater than the long term average (Bureau of Meteorology, 2004b), however further analysis revealed that the distribution of rainfall may have contributed to the enhanced growth. Rainfall during June and July was 23% greater than the long-term average, this corresponded to the period when the major bud flush and height growth are known to occur (Hopkins, 1999a, 1999b). Rainfall during the drier months was up to 178% greater than the long-term average.

This highlights the importance of not only the amount of rainfall, but also the distribution of rainfall upon growth trends.

Cumulative growing season rainfall was found to significantly influence tree growth-ring width and could explain up to 51% of the growth trends. The Pinjar plantation study sites were found to be slightly more responsive to rainfall however the difference between the Gnangara and Pinjar plantation sites was insignificant. The statistical comparison between climate and growth used climate data for the Perth meteorological station (Bureau of Meteorology, 2004b). If site-specific climate data were available then it is likely that the correlations would be stronger (February & Stock, 1998b).

At the Pinjar plantation study sites the enhanced growth response to rainfall may be attributed to the soil properties and rooting depth upon the Spearwood Dune Complex. There is a paucity of data pertaining to the root architecture of *Pinus pinaster* plantations occurring on the Gnangara Mound, although it is likely that the majority of root concentration at both sites will be in the top 20-40cm (Danjon *et al.*, 1999). *Pinus pinaster* Ait. typically forms a single taproot and at the Pinjar plantation sites may extend down to 7m through the soil profile (Butcher, 1977). The taproot of trees located on the Gnangara plantation sites are likely to terminate at the confining layer and be relatively short and thick (Danjon *et al.*, 1999).

A study undertaken by Butcher (1977) of a *Pinus pinaster* Ait. plantation in Yanchep, Western Australia found that the soil wetting front extend up to 6m below the surface. The soil conditions at the study sites were characterised by deep sands of the Spearwood Dune Complex and depth to groundwater was about 16m. The site conditions at the Yanchep study were similar to those of the current Pinjar plantation study sites, indicating that soil moisture at the Pinjar sites is potentially available at depth.

In the shallow soil profile of the Gnangara sites, infiltrated water may perch on the confining layer and either be taken up by plants and transpired, or move laterally along the confining layer towards lower elevations (Davidson, 1995). Consequently

soil moisture at the Gnangara sites may be depleted more rapidly than at the Pinjar sites.

Thinning treatments reduce the interception of rainfall and have been found to increase the effective rainfall by up to 20% (Butcher, 1977), thus increasing soil moisture and increasing the length of the growing season (Hopkins, 1999a). The greater depth of the soil horizon at the Pinjar plantation sites means that potentially greater amounts of water are available for greater periods of time, particularly after thinning treatments. It would appear therefore that soil properties and the availability of soil moisture are the primary influences upon tree growth responses to rainfall, rather than the availability of groundwater resources.

5.1.2 The application of $\delta^{13}C$ as an indicator of historical water availability

This study found that there were no consistent tree growth-ring $\delta^{13}C$ trends with regards to historical climate and groundwater trends. Silviculture was found to significantly influence $\delta^{13}C$ values however the $\delta^{13}C$ responses to silvicultural treatments were not consistent. Thus $\delta^{13}C$ was not an appropriate indicator of water availability. The integration of $\delta^{13}C$ analysis of tree growth-rings did however enhance the interpretation of the influence of historical climate, groundwater trends, and silvicultural treatments upon growth.

The two old sites (>25 years old) in the Gnangara plantation (GN1965a and GN1965b), described above, are located relatively close to each other and have a similar history of silvicultural treatments. However these sites expressed different growth responses to silvicultural treatments. The integration of growth trends with $\delta^{13}C$ results helped to generate a hypothesis to explain the differences. The hypothesis being that historically, periods of waterlogging has led to root-induced stomatal closure (Dubos & Plomion, 2003), resulting in increased $\delta^{13}C$ values and decreased growth responses to thinning treatments.

At these study sites, growth significantly correlated to cumulative growing season rainfall and explained 33% of the growth trends at site GN1965a, and 27% at site

GN1965b. The $\delta^{13}C$ trends were however significantly different. At site GN1965a, maximum depth to groundwater could explain 42% of the $\delta^{13}C$ trends. A negative relationship was identified between depth to groundwater and $\delta^{13}C$, indicating that as the depth to groundwater decreased (i.e. became close to the surface) the $\delta^{13}C$ values became more positive. Growth trends and $\delta^{13}C$ values at site GN1965a may indicate that historically, elevated groundwater levels may have induced stomatal closure and inhibited growth (Danjon *et al.*, 1999). Thus thinning treatments which enhance light infiltration and recharge of the shallow aquifer were not effective in increasing resource availability at site GN1965a.

Conversely at site GN1965b maximum depth to groundwater could only explain 14% of the $\delta^{13}C$ trends, and cumulative growing season rainfall also could explain 14% of the $\delta^{13}C$ trends. Together rainfall and groundwater trends could explain 26% of the $\delta^{13}C$ trends. A positive correlation was observed between the mean maximum depth to groundwater and $\delta^{13}C$ at site GN1965b, indicating that as depth to groundwater increased (i.e. greater depth from the surface), $\delta^{13}C$ became less negative. From these results it may be inferred that historically these trees may have accessed shallow groundwater resources, but as groundwater levels declined these trees became more water use efficient (i.e. increased $\delta^{13}C$). However only 14% of the $\delta^{13}C$ trends at site GN1965b could be explained by maximum depth to groundwater trends therefore the determination of water source partitioning is difficult to validate.

The delineation between the influences of shallow groundwater trends and historical rainfall upon growth trends and $\delta^{13}C$ is difficult because essentially they are collinear (Davidson, 1995). Therefore it is recommended that $\delta^{13}C$ measurements be integrated with the analysis of other stable isotopes such $\delta^{2}H$ and $\delta^{18}O$ to identify water source partitioning.

5.1.3 Conclusion

The application of traditional dendrochronology techniques provided an invaluable resource to evaluate the influence of historical climate, groundwater trends and silvicultural treatments upon growth trends. The analysis of annual growth trends were appropriate for this study, however the use of other dendrochronology techniques, such as the use of scanners and x-ray devices (Schweingruber, 1988), may enhance the temporal resolution. Therefore enabling the delineation of seasonal trends and the influence of historical climate and groundwater trends at finer temporal scales.

This study identified that growth of *Pinus pinaster* Ait. is significantly influenced by both the total rainfall and its distribution. This may be particularly important given the recent changes to climate in Western Australia. Since the mind 1970's the winter rainfall has declined sharply, the late winter rainfall has increased moderately, and day-time and night-time temperatures increased (Indian Ocean Climate Initiative Panel, 2002). Material for chronology development is easily obtained and samples can be acquired regularly during thinning treatments or clear-felling programs, thus the ongoing evaluation of historical growth trends through interpretation of tree growth-rings may enhance the development of future forest management programs in light of future climate predictions.

This study reiterates the difficulties associated with the application of stable carbon isotope analysis to natural environments (Bert *et al.*, 1997; Valentine, 2000). The complexity of the process influencing fractionation means that determining the influence of individual factors upon $\delta^{13}C$ is problematic. Therefore $\delta^{13}C$ cannot be broadly applied as an indicator of water availability in uncontrolled environments (Stewart, Turnbull, Schmidt, & Erskine, 1995; Le Roux, Stock, Bond, & Maphanga, 1996; February & Stock, 1999). The application of $\delta^{13}C$ analysis however can be further enhanced by increasing the temporal resolution by analysing seasonal, rather than annual trends and also considering other site-specific factors influencing ^{13}C discrimination such as light interception (Berry *et al.*, 1997), soil moisture (Walcroft *et al.*, 1997), soil nutrients (Guehl *et al.*, 1995), and the composition of atmospheric carbon dioxide (February & Stock, 1999).

The applicability of stable isotope techniques and dendrochronology techniques used in this study have proven difficult to apply to native vegetation communities on the Swan Coastal Plain (Valentine, 2000). The primary difficulty associated using native species for chronology development is the lack of clearly defined annual growth rings, missing or false rings, and influence of fire and insect attack (February & Stock, 1998a; Argent, McMahon, Bowler, & Finlayson, 2004). The concept of cross-dating signature years is essential to the science of dendrochronology (Fritts, 1967, 1976; Schweingruber, 1988; Cook *et al.*, 1990). The development of chronologies from exotic species, such as *Pinus pinaster* Ait., may provide a useful tool for cross-referencing tree growth-rings signatures between exotic species and native species to facilitate tree growth-ring dating (P. Drake, pers. comm., 5 November, 2004). This in turn may enhance the understanding of the influence of climate and groundwater regimes upon native species.

In conclusion, this study found through the analysis of tree growth-rings, that growth trends of *Pinus pinaster* Ait., occurring on the Gnangara Mound, are significantly influenced by rainfall and silvicultural treatments. Differences between growth trends at the Gnangara and Pinjar plantations were most likely attributed to site-specific soil conditions, microclimate variability and the heterogeneity of silvicultural treatments, rather than the presence or absence of a shallow groundwater resource. Therefore the hypothesis that *Pinus pinaster* Ait. plantations do not directly access shallow groundwater resources could not be validated.

The historical growth trends and $\delta^{13}C$ results from this study will form the basis for evaluating the seasonal and historical groundwater use *Pinus pinaster* Ait. On-going research will be integrating these findings with the analysis of the stable isotopes $\delta^{18}O$ and $\delta^{2}H$ in stem material, gas exchange measurements, instantaneous water use efficiency measurements, and pre-dawn and mid-day xylem pressure potentials. This integrated research approach will enhance the ability of water resource managers and forest managers to implement management strategies to maintain the groundwater resources of the Gnangara Mound in a sustainable manner.

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APPENDICES

APPENDIX 1: Tree growth-ring incremental measurements from *Pinus pinaster* trees sampled from the Gnangara and Pinjar plantations. Site GN1965a

	GN1965a							
	1c1	1c1	1c2	1c2	1c3	1c3	1c4	1c4
	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood
1965								
1966								
1967	10.26	8.03						
1968	15.48	6.58	8.98	7.93				
1969	10.96	7.26	9.95	7.87	6.18	6.70	8.38	5.69
1970	10.31	13.94	8.24	12.34	7.86	10.64	9.09	11.94
1971	7.35	31.56	5.86	20.10	11.19	7.99	10.16	11.51
1972	8.46	31.32	6.40	24.89	7.15	16.24	8.79	19.46
1973	8.45	34.90	5.70	29.24	7.43	22.89	7.26	26.67
1974	8.31	29.54	5.65	26.47	6.28	19.04	8.51	23.24
1975	5.64	33.60	4.60	25.28	4.35	17.61	6.80	32.25
1976	4.38	32.03	3.49	22.30	1.28	26.91	5.35	18.82
1977	3.74	35.47	3.10	27.03	1.88	26.00	4.25	21.95
1978	3.30	37.84	3.28	48.95	2.53	28.20	3.64	25.33
1979	3.05	38.15	2.49	35.47	1.89	27.28	3.04	22.86
1980	2.80	37.56	2.10	39.91	2.03	26.08	1.86	46.25
1981	2.40	43.26	5.68	48.80	3.09	38.41	2.05	40.13
1982	3.84	53.30	5.08	52.82	2.28	27.30	1.31	23.07
1983	4.93	42.26	6.54	44.94	3.33	32.45	3.35	44.91
1984	6.73	44.83	5.09	44.58	3.23	27.41	2.36	34.38
1985	6.00	48.38	4.64	49.03	3.26	36.53	2.99	36.06
1986	5.39	49.46	3.76	46.90	3.63	28.12	2.14	36.12
1987	4.95	46.89	3.90	46.96	3.10	37.11	1.86	54.21
1988	5.64	52.74	3.80	55.47	2.66	36.71	1.63	41.97
1989	3.81	45.20	3.99	42.75	3.26	34.47	1.75	40.78
1990	3.88	41.45	2.86	28.63	3.08	26.71	2.06	31.67
1991	4.53	48.12	4.00	47.21	5.10	46.08	2.25	49.33
1992	4.30	48.43	4.89	64.98	4.08	50.62	2.73	51.31
1993	3.45	54.63	5.53	53.63	3.94	40.89	2.51	40.73
1994	3.90	50.21	4.54	42.64	3.80	28.67	2.83	27.70
1995	5.19	43.62	6.68	55.23	5.55	33.95	5.38	30.46
1996	6.73	51.78	6.93	57.10	5.25	43.87	6.93	30.45
1997	4.04	48.90	4.56	46.86	2.93	32.63	3.10	50.79
1998	3.76	55.84	3.54	53.91	2.33	39.11	3.89	55.04
1999	4.85	55.66	4.13	60.89	2.58	43.26	3.73	47.97
2000	3.40	44.28	2.48	56.91	1.51	31.75	2.10	40.35
2001	2.86	54.14	1.96	49.48	1.55	35.53	2.10	47.28
2002	4.33	53.26	2.34	48.15	1.41	49.16	2.76	39.37
2003	4.60	53.57	2.68	44.17	2.31	30.84	2.85	28.11

APPENDIX 2: Tree growth-ring incremental measurements from *Pinus pinaster* trees sampled from the Gnangara and Pinjar plantations. Site GN1991

	GN1991							
	2al	2al	2a2	2a2	2a3	2a3	2a4	2a4
	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood
1965								
1966								
1967								
1968								
1969								
1970								
1971								
1972								
1973								
1974								
1975								
1976								
1977								
1978								
1979								
1980								
1981								
1982								
1983								
1984								
1985								
1986								
1987								
1988								
1989								
1990								
1991								
1992								
1993					14.24	21.99	9.76	41.87
1994			3.59	67.11	7.83	30.89	8.13	31.29
1995	7.89	12.56	8.39	17.72	5.24	24.45	8.50	21.62
1996	7.89	14.89	8.50	19.36	3.60	37.22	5.01	24.99
1997	4.13	29.99	5.95	29.27	2.99	38.35	3.79	33.45
1998	3.78	28.33	5.14	28.40	2.93	39.89	3.94	27.80
1999	2.63	29.14	4.16	31.76	3.41	39.88	3.69	29.68
2000	2.11	27.90	3.39	29.66	2.75	29.98	3.08	26.54
2001	2.41	33.38	3.20	29.56	2.49	33.80	3.16	27.21
2002	2.38	31.83	2.70	30.92	1.94	35.55	3.15	33.93
2003	2.25	32.92	3.11	35.19	2.14	38.43	3.46	34.65

APPENDIX 3: Tree growth-ring incremental measurements from *Pinus pinaster* trees sampled from the Gnangara and Pinjar plantations. Site GN1985

	GN1985							
	2b5	2b5	2b6	2b6	2b7	2b7	2b8	2b8
	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood
1965								
1966								
1967								
1968								
1969								
1970								
1971								
1972								
1973								
1974								
1975								
1976								
1977								
1978								
1979								
1980								
1981								
1982								
1983								
1984								
1985								
1986								
1987								
1988	11.16	9.30	9.16	10.38	9.43	7.69	8.48	9.53
1989	13.25	14.57	14.05	9.20	9.68	14.71	10.48	12.20
1990	8.93	19.90	10.06	21.74	7.68	23.83	8.85	20.80
1991	11.68	17.56	13.16	15.52	12.30	14.29	10.30	16.27
1992	7.73	23.39	8.44	14.79	7.75	18.39	6.66	19.82
1993	4.88	21.91	5.66	18.39	5.25	24.83	5.29	19.35
1994	4.58	26.87	4.28	18.31	4.36	24.54	4.56	19.72
1995	4.69	27.55	3.86	19.54	4.66	34.02	4.09	29.52
1996	6.26	40.58	5.64	25.12	6.50	31.59	5.75	26.64
1997	4.21	30.13	4.06	24.51	4.56	27.64	3.69	25.31
1998	3.29	42.65	2.90	31.84	2.75	43.91	2.94	31.24
1999	3.38	45.18	3.13	39.14	3.31	42.61	3.29	39.13
2000	1.79	39.75	2.16	26.97	2.53	29.57	2.69	33.99
2001	1.11	45.56	2.03	25.63	1.76	31.96	2.44	34.56
2002	0.78	38.63	1.40	29.25	1.13	40.12	1.15	33.12
2003	0.78	36.96	1.31	32.21	0.96	39.29	1.18	31.44

APPENDIX 4: Tree growth-ring incremental measurements from *Pinus pinaster* trees sampled from the Gnangara and Pinjar plantations. Site GN1965b

	GN1965b							
	2c1	2c1	2c2	2c2	2c3	2c3	2c4	2c4
	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood	Annual Mean (mm)	Mean % Latewood
1965								
1966	6.90	11.59			5.80	21.79		
1967	12.16	7.31	11.58	7.70	11.89	6.86	8.03	8.14
1968	8.50	11.72	12.19	15.69	9.63	10.46	7.39	17.88
1969	5.30	22.28	7.14	15.70	7.43	22.97	4.40	33.58
1970	4.44	22.31	5.65	19.26	5.28	22.51	3.21	43.19
1971	5.66	20.58	7.19	23.86	8.89	30.36	6.89	24.47
1972	6.23	22.08	8.14	20.98	10.05	35.93	7.31	35.13
1973	5.55	35.05	7.23	31.16	6.75	44.44	5.93	44.79
1974	4.96	31.51	5.99	23.82	5.55	32.82	4.40	43.96
1975	4.33	24.15	4.30	28.11	3.78	29.53	3.16	38.71
1976	3.43	27.03	3.05	26.99	2.38	29.91	2.06	42.80
1977	2.64	32.88	2.66	43.78	1.81	39.27	2.00	38.97
1978	3.01	38.31	3.91	47.09	1.74	50.43	2.38	47.99
1979	2.64	36.53	3.16	34.69	1.58	46.16	1.85	47.93
1980	1.59	48.93	2.24	49.50	1.30	57.83	1.70	51.22
1981	2.11	45.07	3.79	46.78	1.66	60.07	1.76	53.53
1982	1.15	56.09	2.38	42.01	1.10	63.90	1.46	42.96
1983	1.23	53.07	2.63	47.15	1.04	65.51	1.34	57.01
1984	1.79	53.46	3.05	54.91	1.33	54.28	1.55	59.38
1985	3.84	65.51	4.60	60.87	1.66	77.61	2.45	62.04
1986	7.80	54.03	7.95	56.67	3.25	61.90	5.51	54.34
1987	8.00	56.72	8.30	39.01	5.30	60.71	7.39	51.12
1988	6.89	49.42	6.73	45.69	5.06	59.54	7.21	43.70
1989	5.41	45.03	5.93	53.64	4.70	67.23	4.81	41.77
1990	4.16	35.51	4.88	42.57	3.39	39.38	2.86	32.13
1991	6.24	46.49	8.70	53.34	8.43	64.45	5.43	53.43
1992	6.31	50.18	6.75	46.12	11.28	64.30	5.03	62.26
1993	4.03	44.10	4.75	51.81	6.89	42.88	3.86	49.08
1994	3.78	36.08	3.86	45.45	5.58	46.02	2.65	50.98
1995	5.34	37.14	6.06	48.05	6.80	53.19	5.53	46.93
1996	5.83	43.26	7.53	48.14	9.14	52.10	4.51	52.63
1997	3.10	44.61	4.13	47.30	4.81	46.35	2.48	57.05
1998	4.56	54.02	4.74	56.40	4.73	62.37	3.29	57.01
1999	3.33	51.34	4.76	60.04	6.04	55.07	3.40	54.92
2000	2.20	40.45	3.04	44.42	3.15	43.47	2.76	57.07
2001	2.50	41.68	2.64	47.49	2.46	57.53	3.01	49.93
2002	2.09	42.95	2.51	46.23	2.65	54.29	2.65	49.00
2003	2.30	36.20	3.46	44.48	4.16	45.38	2.95	49.98

APPENDIX 5: Tree growth-ring incremental measurements from *Pinus pinaster* trees sampled from the Gnangara and Pinjar plantations. Site PJ1995

	PJ1995							
	3a1 Annual Mean (mm)	3a1 Mean % Latewood	3a2 Annual Mean (mm)	3a2 Mean % Latewood	3a3 Annual Mean (mm)	3a3 Mean % Latewood	3a4 Annual Mean (mm)	3a4 Mean % Latewood
1965								
1966								
1967								
1968								
1969								
1970								
1971								
1972								
1973								
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1990								
1991								
1992								
1993								
1994								
1995								
1996	2.11	26.56	3.09	21.19	6.04	14.18	2.25	26.82
1997	4.60	44.50	8.85	29.21	7.71	41.50	6.03	35.71
1998	11.89	18.25	11.25	39.25	13.31	19.18	10.26	18.05
1999	10.83	27.19	11.20	27.04	11.09	30.33	12.93	27.08
2000	8.31	28.84	7.19	24.54	7.30	29.28	8.21	33.21
2001	6.88	34.93	6.76	36.10	7.49	36.45	6.54	29.80
2002	6.43	29.15	5.73	32.31	6.14	35.65	5.54	27.41
2003	5.73	17.12	6.04	18.31	5.73	16.63	5.23	13.30

APPENDIX 6: Tree growth-ring incremental measurements from *Pinus pinaster* trees sampled from the Gnangara and Pinjar plantations. Site PJ1982

PJ1982

	3b1 Annual Mean (mm)	3b1 Mean % Latewood	3b2 Annual Mean (mm)	3b2 Mean % Latewood	3b3 Annual Mean (mm)	3b3 Mean % Latewood	3b4 Annual Mean (mm)	3b4 Mean % Latewood
1965								
1966								
1967								
1968								
1969								
1970								
1971								
1972								
1973								
1974								
1975								
1976								
1977								
1978								
1979								
1980								
1981								
1982								
1983							7.38	15.30
1984	8.76	10.83	4.29	8.73	9.89	7.08	10.13	11.41
1985	13.10	10.54	11.41	6.66	14.88	10.45	10.39	21.46
1986	12.06	29.61	11.33	9.63	10.71	19.50	7.93	16.65
1987	10.29	33.73	7.90	16.86	6.29	31.19	6.70	20.77
1988	8.58	40.35	7.94	21.06	6.51	23.58	6.29	25.70
1989	7.76	30.10	7.60	17.77	5.49	31.32	6.44	29.85
1990	5.51	39.72	4.61	22.92	3.99	24.90	4.63	22.48
1991	7.49	31.24	7.25	24.74	5.13	26.68	7.85	22.62
1992	5.15	33.31	4.70	29.24	2.93	29.63	4.19	32.82
1993	4.03	15.91	3.64	19.24	2.84	26.67	3.69	18.83
1994	4.13	23.57	4.08	13.04	2.61	25.39	3.18	21.49
1995	5.51	27.24	4.75	14.93	2.31	36.68	4.54	22.18
1996	6.36	29.85	5.69	19.96	3.78	40.79	5.08	33.16
1997	3.35	37.11	3.79	23.75	3.00	29.51	2.99	41.74
1998	4.41	46.82	3.56	38.72	4.11	47.45	4.85	50.33
1999	5.28	29.82	3.89	39.29	4.56	31.94	4.55	33.93
2000	7.76	44.11	6.71	33.71	7.71	30.03	5.86	38.93
2001	10.85	34.10	10.34	27.35	9.86	24.90	8.23	36.10
2002	10.84	39.28	13.16	32.57	13.05	23.69	10.19	30.04
2003	10.36	22.28	11.55	13.11	9.66	20.21	9.46	22.45

APPENDIX 7: Tree growth-ring incremental measurements from *Pinus pinaster* trees sampled from the Gnangara and Pinjar plantations. Site PJ1971

	PJ1971							
	3c1 Annual Mean (mm)	3c1 Mean % Latewood	3c2 Annual Mean (mm)	3c2 Mean % Latewood	3c3 Annual Mean (mm)	3c3 Mean % Latewood	3c4 Annual Mean (mm)	3c4 Mean % Latewood
1965								
1966								
1967								
1968								
1969								
1970								
1971								
1972								
1973	10.40	7.80						
1974	12.58	8.07	14.16	6.44	10.76	7.30	12.60	4.58
1975	12.60	11.51	13.81	10.00	9.69	9.15	13.68	7.98
1976	7.40	21.54	7.19	13.14	5.70	14.37	8.98	10.67
1977	5.91	21.90	5.48	19.13	3.85	27.91	6.14	17.89
1978	5.65	21.48	6.60	17.83	4.14	35.20	6.19	25.39
1979	5.75	28.80	6.19	21.26	3.29	35.98	4.89	32.36
1980	4.95	31.06	5.14	17.89	3.48	27.32	4.64	31.31
1981	4.93	40.15	5.56	22.31	3.94	36.90	4.59	35.37
1982	3.09	35.26	5.03	28.95	3.05	39.79	4.28	44.72
1983	3.13	40.05	5.65	31.57	3.58	35.68	4.09	40.59
1984	2.68	36.25	5.03	39.36	3.33	39.52	3.49	41.99
1985	2.54	50.46	4.96	32.90	3.70	42.92	2.76	49.79
1986	1.75	39.23	3.10	33.03	2.44	47.11	1.98	48.95
1987	3.14	46.21	2.95	40.70	2.31	51.12	1.85	50.39
1988	6.04	31.80	4.81	33.83	5.05	43.07	3.18	35.70
1989	7.31	39.58	6.41	42.01	5.34	43.20	3.61	43.53
1990	4.58	26.25	4.84	26.07	4.73	23.87	2.94	34.51
1991	6.15	29.15	7.93	33.41	8.31	29.92	4.95	35.45
1992	4.76	12.59	6.71	28.92	5.98	29.93	3.70	27.96
1993	4.90	18.60	5.35	31.00	6.36	33.24	3.38	30.87
1994	4.70	16.71	5.24	28.67	6.59	33.58	2.15	34.50
1995	7.39	18.62	6.55	35.93	9.35	29.80	2.61	34.02
1996	8.85	25.39	7.00	33.86	12.90	33.70	3.59	38.22
1997	5.65	35.69	5.34	34.41	4.78	40.39	3.60	34.92
1998	6.29	37.98	5.86	49.09	4.26	58.78	4.64	41.84
1999	6.18	29.13	6.85	40.53	4.86	32.37	4.84	36.24
2000	3.58	24.76	3.24	26.53	2.28	39.54	3.29	27.84
2001	3.30	41.50	4.63	36.15	2.91	48.49	4.28	40.39
2002	2.41	28.83	2.83	27.40	2.75	34.07	3.20	30.90
2003	3.20	27.75	2.73	30.89	2.75	36.13	3.81	28.60

APPENDIX 8: Sample weights and sample recovery results from the cellulose extraction procedure using the modified di-glyme procedure (Macfarlane *et al*, 1999)

ID	Initial Weight (g)	Crucible ID	Crucible weight (g)	Post weight (g)	Material recovery (%)
1c476	0.10	1.00	22.47	22.52	49.47
1c477	0.09	2.00	21.54	21.58	45.35
1c478	0.05	3.00	22.71	22.74	46.00
1c479	0.12	4.00	21.66	21.72	50.42
1c480	0.10	5.00	20.26	20.31	52.53
1c483	0.06	6.00	20.39	20.42	46.55
1c484	0.03	7.00	23.70	23.72	46.43
1c485	0.04	8.00	22.34	22.36	44.74
1c486	0.07	9.00	21.39	21.43	52.11
1c487	0.04	10.00	20.92	20.94	54.76
1c495	0.11	11.00	0.32	0.37	46.22
1c496	0.11	12.00	0.33	0.37	38.04
1c497	0.15	13.00	0.32	0.40	51.24
1c498	0.07	14.00	0.33	-	-
1c499	0.08	15.00	0.33	0.36	43.15
2c176	0.15	21.00	0.33	0.40	48.02
2c177	0.07	22.00	0.32	0.36	58.92
2c178	0.06	23.00	0.32	0.35	42.29
2c179	0.05	24.00	0.33	0.35	41.52
2c180	2.05	25.00	0.32	0.34	1.02
2c183	0.04	26.00	0.32	0.34	38.07
2c184	0.04	27.00	0.33	0.35	37.50
2c185	0.13	28.00	0.32	0.39	49.54
2c186	0.13	29.00	0.31	0.38	51.09
2c187	0.19	30.00	0.32	0.42	52.28
2c195	0.16	31.00	0.32	0.39	49.12
2c196	0.16	32.00	0.32	0.40	51.51
2c197	0.12	33.00	0.32	0.37	41.08
2c198	0.14	34.00	0.32	0.38	46.68
2c199	0.17	35.00	0.32	0.41	52.05
3c276	0.11	36.00	0.33	0.37	37.86
3c277	0.06	37.00	0.31	0.34	45.87
3c278	0.08	38.00	0.32	0.35	35.84
3c279	0.07	39.00	0.33	0.36	35.64
3c280	0.08	40.00	0.32	0.35	33.62
3c283	0.09	41.00	0.32	0.35	33.26
3c284	0.05	42.00	0.33	0.34	33.48
3c285	0.08	43.00	0.32	0.35	42.74
3c286	0.07	44.00	0.32	0.34	38.05
3c287	0.09	45.00	0.33	0.37	40.97
3c295	0.09	46.00	0.32	0.35	43.68
3c296	0.08	47.00	0.32	0.35	41.38
3c297	0.07	48.00	0.33	0.36	40.44
3c298	0.13	49.00	0.33	0.39	48.08
3c299	0.08	50.00	0.32	0.36	43.80
3b284	0.06	16.00	0.32	0.33	20.07
3b285	0.10	17.00	0.32	0.34	27.30
3b290	0.05	18.00	0.33	0.35	35.85
3b296	0.09	19.00	0.32	0.35	37.13
3b203	0.17	20.00	0.32	0.40	46.00

APPENDIX 9: Analysis of tree growth-rings $\delta^{13}C$ results from *Pinus pinaster* Ait. using the modified di-glyme procedure (Macfarlane *et al*, 1999) for the extraction of crude cellulose

Date	ID	%c	whole wood d13c	ID	%c	Crude cellulose d13c	Difference	lignin adjusted (0.3per mil bias)
1976	736	45.59	-24.37	982	42.53	-23.85	0.53	-23.55
1977	737	45.90	-23.91	983	41.86	-23.59	0.32	-23.29
1978	738	44.79	-23.55	984	41.93	-23.02	0.53	-22.72
1979	739	45.77	-24.00	985	42.32	-23.90	0.10	-23.60
1980	740	44.81	-22.89	986	42.97	-22.41	0.48	-22.11
1983	743	45.36	-23.33	987	39.12	-22.74	0.58	-22.44
1985	745	44.48	-23.81	988	37.56	-23.36	0.45	-23.06
1986	746	43.86	-23.14	989	42.24	-22.52	0.62	-22.22
1987	747	44.51	-23.88	990	40.38	-23.24	0.64	-22.94
1995	755	45.32	-23.55	991	40.47	-23.32	0.23	-23.02
1996	756	45.13	-22.94	992	42.71	-22.28	0.65	-21.98
1997	757	45.28	-23.52	993	43.54	-23.01	0.51	-22.71
1999	759	45.49	-23.17	994	42.00	-22.58	0.60	-22.28
1976	464	45.02	-24.06	995	42.60	-23.97	0.09	-23.67
1977	465	45.09	-24.67	996	42.67	-24.22	0.44	-23.92
1978	466	45.60	-23.38	997	42.35	-22.80	0.57	-22.50
1979	467	45.16	-24.54	998	42.30	-24.09	0.46	-23.79
1980	468	45.12	-24.81	999	42.26	-24.53	0.28	-24.23
1983	471	44.22	-24.75	1000	42.43	-24.18	0.56	-23.88
1985	473	45.36	-24.01	1001	43.74	-23.63	0.38	-23.33
1986	474	46.14	-23.16	1002	44.08	-23.51	-0.35	-23.21
1987	475	45.46	-24.04	1003	42.35	-23.88	0.17	-23.58
1995	483	47.40	-24.95	1004	42.92	-24.46	0.49	-24.16
1996	484	47.24	-25.23	1005	42.84	-24.54	0.69	-24.24
1997	485	47.00	-25.29	1006	42.89	-24.84	0.45	-24.54
1998	486	46.96	-24.50	1007	42.78	-23.54	0.96	-23.24
1999	487	46.37	-25.52	1008	42.48	-25.16	0.36	-24.86
1976	561	46.58	-22.53	1009	43.63	-21.90	0.63	-21.60
1977	562	45.72	-23.29	1010	41.60	-21.73	1.56	-21.43
1978	563	45.98	-23.35	1011	42.10	-22.31	1.04	-22.01
1979	564	46.88	-23.27	1012	42.52	-22.07	1.21	-21.77
1980	565	45.14	-23.74	1013	43.53	-23.10	0.64	-22.80
1983	568	45.52	-24.13	1014	42.71	-22.80	1.33	-22.50
1984	569	45.77	-23.56	1015	40.59	-22.79	0.77	-22.49
1985	570	46.32	-24.50	1016	42.82	-23.69	0.81	-23.39
1986	571	45.96	-24.08	1017	42.80	-22.36	1.72	-22.06
1987	572	46.35	-24.38	1018	42.27	-23.72	0.66	-23.42
1995	580	45.5	-23.94	1019	41.44	-23.00	0.95	-22.70
1996	581	46.38	-23.49	1020	41.69	-22.69	0.80	-22.39
1997	582	46.02	-23.94	1021	42.56	-23.38	0.57	-23.08
1998	583	44.89	-24.65	1022	42.74	-23.53	1.12	-23.23
1999	584	45.73	-23.65	1023	42.98	-22.96	0.69	-22.66
1984	831	46.52	-24.60	1024	42.97	-24.06	0.54	-23.76
1985	832	47.75	-25.19	1025	41.86	-24.64	0.54	-24.34
1990	837	44.84	-25.24	1026	42.50	-24.89	0.35	-24.59
1996	843	45.55	-25.66	1027	41.57	-25.32	0.34	-25.02
2003	850	45.43	-24.71	1028	44.43	-24.37	0.34	-24.07

APPENDIX 10: Analysis of $\delta^{13}C$ of *Pinus pinaster* Ait. tree growth-rings. Site GN1965a

	1c1 (GN1965a)			1c2 (GN1965a)			1c3 (GN1965a)			1c4 (GN1965a)		
Year	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C
1966												
1967	492	47.86	-25.64									
1968	493	47.85	-25.38	381	47.21	-24.93						
1969	494	46.91	-24.76	382	46.62	-24.18	589	45.67	-23.57	729	47.04	-23.73
1970	495	47.30	-24.98	383	47.82	-24.27	590	47.19	-24.03	730	46.66	-22.57
1971	496	46.96	-25.19	384	46.96	-24.33	591	46.69	-23.46	731	45.60	-22.52
1972	497	47.47	-24.12	385	45.35	-24.09	592	46.93	-23.99	732	46.51	-21.71
1973	498	46.47	-26.35	386	45.49	-24.76	593	47.51	-25.02	733	45.23	-22.49
1974	499	46.86	-25.83	387	45.10	-25.26	594	46.69	-25.23	734	45.80	-23.04
1975	500	45.64	-25.34	388	46.16	-24.59	595	45.84	-24.48	735	46.25	-24.54
1976	501	46.07	-25.22	389	45.29	-24.30	596	45.27	-24.32	736	45.59	-24.37
1977	502	46.48	-25.54	390	45.13	-25.08	597	46.35	-25.37	737	45.90	-23.91
1978	503	45.35	-25.30	391	45.40	-24.04	598	46.19	-24.30	738	44.79	-23.55
1979	504	45.73	-24.71	392	44.37	-24.19	599	45.63	-25.18	739	45.77	-24.00
1980	505	46.88	-25.13	393	45.27	-24.84	600	46.12	-24.70	740	44.81	-22.89
1981	506	46.31	-24.25	394	45.88	-24.14	601	45.81	-24.91	741	45.66	-23.77
1982	507	47.53	-23.72	395	45.22	-23.47	602	46.00	-24.44	742	44.45	-23.66
1983	508	47.07	-25.08	396	45.58	-24.57	603	45.32	-25.28	743	45.36	-23.33
1984	509	47.21	-25.04	397	45.40	-24.30	604	45.79	-24.84	744	44.77	-22.98
1985	510	46.38	-26.35	398	45.20	-24.13	605	46.20	-25.63	745	44.48	-23.81
1986	511	46.57	-25.51	399	45.17	-24.55	606	nd	nd	746	43.86	-23.14
1987	512	47.19	-25.70	400	44.69	-25.47	607	nd	nd	747	44.51	-23.88
1988	513	46.79	-25.41	401	43.85	-24.32	608	nd	nd	748	43.65	-24.38
1989	514	45.10	-25.74	402	45.14	-24.36	609	44.63	-25.35	749	44.36	-24.85
1990	515	46.06	-25.04	403	44.85	-24.85	610	43.71	-25.28	750	44.44	-24.24
1991	516	47.22	-25.43	404	45.33	-25.31	611	43.96	-25.35	751	45.05	-23.11
1992	517	46.34	-25.38	405	44.81	-24.61	612	45.17	-24.55	752	44.93	-24.22
1993	518	47.04	-24.22	406	46.00	-23.84	613	44.20	-24.54	753	44.95	-23.49
1994	519	46.29	-24.35	407	46.04	-24.07	614	43.47	-24.53	754	45.00	-23.35
1995	520	45.76	-24.85	408	46.54	-24.24	615	44.29	-24.20	755	45.32	-23.55
1996	521	47.02	-25.55	409	45.98	-25.19	616	44.51	-25.33	756	45.13	-22.94
1997	522	47.25	-25.45	410	47.26	-24.80	617	42.85	-25.32	757	45.28	-23.52
1998	523	47.13	-25.82	411	46.46	-24.93	618	44.39	-25.28	758	45.43	-23.27
1999	524	46.82	-25.85	412	47.17	-25.18	619	43.02	-25.04	759	45.49	-23.17
2000	525	47.30	-25.56	413	46.99	-24.55	620	43.53	-25.60	760	45.16	-23.88
2001	526	46.58	-25.67	414	45.37	-24.69	621	44.31	-25.74	761	44.79	-24.50
2002	527	47.30	-26.06	415	45.15	-24.97	622	43.20	-25.17	762	45.10	-24.36
2003	528	46.22	-26.11	416	45.05	-24.87	623	42.94	-25.55	763	44.04	-24.00
Average			-25.29			-24.56			-24.86			-23.56
Stdev			0.10			0.08			0.11			0.12
Count		37			36			32			35	

APPENDIX 11: Analysis of $\delta^{13}C$ of *Pinus pinaster* Ait. tree growth-rings. Site GN1991

	2a1			2a2			2a3			2a4		
Year	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C
1966												
1967												
1968												
1969												
1970												
1971												
1972												
1973												
1974												
1975												
1976												
1977												
1978												
1979												
1980												
1981												
1982												
1983												
1984												
1985												
1986												
1987												
1988												
1989												
1990												
1991												
1992												
1993							911	46.52	-25.79	955	45.51	-24.69
1994				805	46.26	-25.71	912	46.08	-26.05	956	46.83	-25.57
1995	930	44.69	-26.56	806	46.54	-25.79	913	46.61	-25.61	957	46.32	-24.47
1996	931	44.65	-26.33	807	45.89	-25.52	914	46.35	-25.45	958	44.94	-25.77
1997	932	44.17	-24.43	808	45.13	-24.55	915	46.13	-25.17	959	43.42	-23.96
1998	933	43.27	-25.69	809	45.71	-25.49	916	45.86	-26.54	960	46.89	-26.25
1999	934	45.75	-26.20	810	45.31	-25.62	917	46.37	-26.23	961	43.99	-25.69
2000	935	44.34	-25.64	811	44.99	-24.58	918	46.82	-25.16	962	45.81	-25.52
2001	936	45.57	-25.80	812	45.43	-24.95	919	46.25	-26.31	963	45.49	-25.67
2002	937	46.45	-25.33	813	45.48	-25.13	920	46.43	-26.10	964	44.65	-25.91
2003	938	40.84	-26.19	814	45.75	-25.38	921	46.72	-26.53	965	43.81	-26.39
Average			-25.80			-25.27			-25.90			-25.45
Stdev			0.21			0.14			0.15			0.23
Count		9			10			11			11	

APPENDIX 12: Analysis of $\delta^{13}C$ of *Pinus pinaster* Ait. tree growth-rings. Site GN1985

	2b5			2b6			2b7			2b8		
Year	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C
1966												
1967												
1968												
1969												
1970												
1971												
1972												
1973												
1974												
1975												
1976												
1977												
1978												
1979												
1980												
1981												
1982												
1983												
1984												
1985												
1986												
1987												
1988	887	50.38	-25.96	851	47.69	-24.59	815	46.74	-23.70	939	46.17	-24.55
1989	888	47.82	-26.24	852	45.47	-24.57	816	45.58	-23.15	940	45.36	-24.43
1990	889	48.04	-24.84	853	46.16	-23.65	817	46.39	-22.31	941	46.06	-24.19
1991	890	47.59	-26.33	854	45.86	-24.53	818	46.67	-23.97	942	44.79	-24.35
1992	891	46.88	-26.12	855	45.96	-23.98	819	46.21	-24.42	943	44.76	-24.86
1993	892	46.76	-26.31	856	46.04	-24.49	820	47.44	-24.28	944	44.87	-24.82
1994	893	47.15	-25.87	857	45.97	-25.24	821	47.02	-24.34	945	44.63	-25.15
1995	894	45.36	-26.71	858	45.83	-25.74	822	46.41	-24.91	946	42.45	-25.90
1996	895	47.43	-26.80	859	46.30	-25.94	823	46.05	-25.22	947	43.93	-26.17
1997	896	46.15	-26.09	860	45.84	-25.43	824	45.51	-25.08	948	44.99	-24.93
1998	897	46.80	-26.31	861	46.22	-25.83	825	46.37	-25.37	949	42.32	-25.94
1999	898	46.23	-26.78	862	46.10	-25.73	826	46.28	-25.35	950	44.31	-25.82
2000	899	46.31	-26.35	863	45.66	-25.93	827	46.03	-25.53	951	44.43	-25.78
2001	900	45.72	-26.37	864	46.16	-25.53	828	45.91	-24.61	952	45.44	-26.18
2002	901	46.22	-25.37	865	46.10	-25.60	829	46.30	-25.25	953	45.49	-25.02
2003	902	45.85	-25.56	866	45.10	-24.08	830	45.29	-25.60	954	43.94	-25.47
Average			-26.13			-25.05			-24.57			-25.22
Stdev			0.13			0.19			0.23			0.17
Count		16			16			16			16	

APPENDIX 13: Analysis of $\delta^{13}C$ of *Pinus pinaster* Ait. tree growth-rings. Site GN1965b

	2c1			2c2			2c3			2c4		
Year	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C
1966	454	48.37	-24.91									
1967	435	47.74	-24.84	417	47.12	-24.87	692	48.13	-26.08	624	44.58	-26.28
1968	456	47.82	-24.08	418	48.27	-24.21	693	48.05	-25.96	625	45.03	-25.75
1969	457	48.71	-23.89		48.48	-23.64	694	47.85	-24.86	626	45.04	-25.31
1970	458	48.46	-25.33		49.89	-24.31	695	45.53	-25.55	627	44.98	-25.85
1971	459	48.02	-23.91	421	48.88	-23.38	696	47.87	-24.49	628	45.28	-24.61
1972	460	46.14	-23.31	422	48.05	-23.28	697	48.30	-23.88	629	44.57	-24.69
1973	461	45.68	-24.32	423	47.53	-24.62	698	48.22	-25.69	630	43.20	-24.89
1974	462	45.97	-24.60	424	47.87	-24.73	699	47.65	-25.83	631	44.52	-25.86
1975	463	45.51	-24.47	425	48.91	-24.44	700	45.56	-25.18	632	42.64	-25.24
1976	464	45.02	-24.06	426	45.35	-23.17	701	45.82	-25.49	633	42.04	-24.58
1977	465	45.09	-24.67	427	45.18	-22.87	702	46.33	-24.88	634	43.87	-24.68
1978	466	45.60	-23.38	428	45.37	-22.33	703	45.77	-24.56	635	43.75	-23.80
1979	467	45.16	-24.54	429	45.53	-23.96	704	45.33	-25.81	636	44.20	-25.08
1980	468	45.12	-24.81	430	44.91	-23.22	705	45.60	-24.60	637	43.50	-24.53
1981	469	44.71	-24.49	431	45.96	-23.37	706	45.84	-24.32	638	42.79	-24.58
1982	470	44.44	-24.72	432	44.73	-23.62	707	46.08	-25.34	639	43.66	-25.31
1983	471	44.22	-24.75	433	44.85	-23.52	708	45.37	-24.22	640	44.00	-25.09
1984	472	45.43	-23.42	434	45.70	-23.67	709	45.76	-24.59	641	43.94	-24.64
1985	473	45.36	-24.01	435	45.52	-23.11	710	45.77	-23.97	642	43.04	-24.46
1986	474	46.14	-23.16	436	45.04	-23.12	711	45.95	-23.70	643	44.89	-23.97
1987	475	45.46	-24.04	437	45.03	-23.54	712	45.24	-24.50	644	44.59	-25.21
1988	476	46.26	-24.74	438	44.49	-23.90	713	46.09	-24.82	645	43.95	-25.34
1989	477	45.74	-25.06	439	44.96	-23.99	714	45.33	-24.05	646	44.92	-24.95
1990	478	47.29	-24.78	440	44.95	-23.54	715	45.28	-23.96	647	45.73	-25.47
1991	479	46.56	-25.67	441	44.94	-24.46	716	45.62	-24.68	648	45.58	-25.81
1992	480	47.19	-24.36	442	45.22	-24.44	717	45.32	-24.63	649	44.43	-24.84
1993	481	47.48	-24.41	443	45.49	-24.09	718	45.62	-23.88	650	44.85	-24.80
1994	482	47.52	-24.96	444	45.82	-23.82	719	45.31	-23.94	651	43.25	-24.69
1995	483	47.40	-24.95	445	45.23	-23.78	720	44.51	-23.61	652	44.30	-23.80
1996	484	47.24	-25.23	446	45.90	-24.28	721	45.73	-24.24	653	44.55	-24.56
1997	485	47.00	-25.29	447	45.17	-24.16	722	45.06	-24.68	654	43.28	-24.98
1998	486	46.96	-24.50	448	44.89	-23.74	723	45.20	-24.08	655	44.27	-25.14
1999	487	46.37	-25.52	449	45.85	-24.06	724	45.51	-24.99	656	44.08	-24.81
2000	488	46.39	-24.95	450	44.77	-24.03	725	44.74	-24.13	657	44.27	-24.31
2001	489	43.85	-24.40	451	45.27	-24.09	726	44.78	-24.84	658	44.25	-24.25
2002	490	45.86	-26.06	452	43.53	-24.09	727	44.58	-23.98	659	44.45	-24.91
2003	491	45.36	-25.13	453	43.44	-23.99	728	44.25	-23.69	660	43.94	-24.63
Average			-24.57			-23.82			-24.64			-24.91
Stdev			0.11			0.09			0.12			0.09
Count		38			37			37			37	

APPENDIX 14: Analysis of $\delta^{13}C$ of *Pinus pinaster* Ait. tree growth-rings. Site PJ1995

	3a1			3a2			3a3			3a4		
Year	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C
1966												
1967												
1968												
1969												
1970												
1971												
1972												
1973												
1974												
1975												
1976												
1977												
1978												
1979												
1980												
1981												
1982												
1983												
1984												
1985												
1986												
1987												
1988												
1989												
1990												
1991												
1992												
1993												
1994												
1995												
1996	974	45.95	-24.12	922	46.23	-26.41	903	46.28	-26.05	966	44.32	-23.69
1997	975	45.30	-25.13	923	45.90	-24.27	904	47.22	-24.19	967	42.20	-24.65
1998	976	46.08	-24.04	924	46.47	-24.43	905	47.04	-24.55	968	45.53	-24.59
1999	977	45.83	-23.77	925	46.53	-24.34	906	46.02	-24.10	969	45.90	-24.76
2000	978	46.11	-23.23	926	42.57	-24.37	907	46.42	-23.77	970	46.21	-23.89
2001	979	45.14	-23.94	927	43.41	-24.76	908	46.41	-24.65	971	44.88	-23.55
2002	980	45.63	-24.76	928	42.83	-25.21	909	46.41	-25.61	972	45.10	-24.26
2003	981	45.08	-24.25	929	44.04	-24.70	910	46.37	-24.82	973	44.47	-24.13
Average			-24.15			-24.81			-24.72			-24.19
Stdev			0.21			0.25			0.27			0.16
Count		8			8			8			8	

APPENDIX 15: Analysis of $\delta^{13}C$ of *Pinus pinaster* Ait. tree growth-rings. Site PJ1982

	3b1			3b2			3b3			3b4		
Year	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C
1966												
1967												
1968												
1969												
1970												
1971												
1972												
1973												
1974												
1975												
1976												
1977												
1978												
1979												
1980												
1981												
1982												
1983										764	52.41	-24.85
1984	785	46.36	-24.26	831	46.52	-24.60	867	48.54	-24.68	765	50.71	-24.02
1985	786	50.71	-25.07	832	47.75	-25.19	868	47.35	-23.89	766	47.33	-24.36
1986	787	49.59	-25.05	833	48.05	-23.82	869	46.28	-22.95	767	44.49	-23.49
1987	788	47.29	-22.66	834	45.84	-24.04	870	45.30	-23.27	768	45.01	-23.23
1988	789	46.47	-23.86	835	45.90	-24.36	871	46.17	-22.93	769	45.33	-24.26
1989	790	46.63	-23.33	836	45.76	-24.95	872	46.49	-24.02	770	45.12	-24.44
1990	791	46.00	-23.44	837	44.84	-25.24	873	45.35	-24.05	771	45.51	-24.33
1991	792	45.86	-24.03	838	46.37	-25.46	874	45.83	-24.30	772	45.13	-24.53
1992	793	46.37	-24.08	839	45.45	-24.31	875	45.76	-24.33	773	45.01	-24.11
1993	794	45.83	-24.01	840	45.71	-24.88	876	45.56	-24.33	774	45.46	-23.86
1994	795	46.09	-24.35	841	45.97	-25.93	877	44.50	-25.27	775	44.44	-25.19
1995	796	45.12	-24.56	842	46.16	-25.60	873	45.45	-24.65	776	45.22	-24.28
1996	797	45.87	-24.57	843	45.55	-25.66	879	45.14	-24.92	777	45.25	-24.61
1997	798	44.70	-25.00	844	45.18	-26.54	880	45.49	-25.55	778	45.55	-24.57
1998	799	45.14	-25.06	845	45.57	-25.00	881	46.37	-24.29	779	45.71	-23.52
1999	800	44.82	-23.93	846	45.81	-25.53	882	46.13	-25.23	780	45.42	-24.76
2000	801	45.41	-24.26	847	45.87	-23.52	883	46.20	-23.06	781	46.09	-22.58
2001	802	46.13	-23.55	848	46.08	-24.14	884	46.72	-23.65	782	45.88	-23.22
2002	803	45.95	-23.97	849	45.68	-25.22	885	46.36	-23.99	783	46.52	-23.20
2003	804	46.43	-24.20	850	45.43	-24.71	886	46.19	-24.07	784	46.43	-23.76
Average			-24.16			-24.93			-24.17			-24.06
Stdev			0.14			0.17			0.17			0.14
Count		20			20			20			21	

APPENDIX 16: Analysis of $\delta^{13}C$ of *Pinus pinaster* Ait. tree growth-rings. Site PJ1971

	3c1			3c2			3c3			3c4		
Year	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C	Sample Title	%C	delta 13C
1966												
1967												
1968												
1969												
1970												
1971												
1972												
1973	661	46.23	-24.61				350	49.65	-23.58			
1974	662	46.02	-24.19	559	46.58	-22.79	351	47.45	-23.07	529	47.62	-24.24
1975	663	47.23	-24.02	560	46.24	-22.93	352	48.59	-22.69	530	49.33	-23.02
1976	664	46.80	-24.56	561	46.58	-22.53	353	47.45	-22.58	531	47.72	-22.73
1977	665	46.03	-24.52	562	45.72	-23.29	354	46.29	-22.97	532	48.19	-23.60
1978	666	47.30	-23.91	563	45.98	-23.35	355	46.30	-23.31	533	47.42	-23.40
1979	667	44.95	-25.00	564	46.88	-23.27	356	47.03	-22.79	534	46.86	-23.16
1980	668	48.24	-24.62	565	45.14	-23.74	357	46.55	-22.88	535	46.81	-24.19
1981	669	50.15	-25.65	566	49.23	-23.56	358	46.12	-23.85	536	46.09	-24.00
1982	670	51.75	-25.61	567	45.09	-23.05	359	45.95	-23.76	537	46.14	-22.91
1983	671	50.36	-25.26	568	45.52	-24.13	360	45.31	-23.89	538	47.05	-23.85
1984	672	49.61	-25.74	569	45.77	-23.56	361	45.63	-23.53	539	46.54	-24.01
1985	673	51.91	-25.59	570	46.32	-24.50	362	45.52	-24.08	540	46.12	-24.41
1986	674	52.18	-25.28	571	45.96	-24.08	363	44.28	-23.64	541	46.94	-23.32
1987	675	51.06	-25.96	572	46.35	-24.38	364	45.27	-22.87	542	45.45	-22.92
1988	676	52.78	-26.45	573	46.77	-25.11	365	45.86	-23.67	543	46.48	-23.20
1989	677	52.59	-26.42	574	46.56	-25.19	366	45.85	-24.47	544	46.11	-23.79
1990	678	48.83	-26.31	575	46.78	-24.83	367	45.61	-25.00	545	43.78	-24.60
1991	679	45.04	-24.84	576	46.39	-24.23	368	45.45	-24.27	546	45.77	-24.26
1992	680	45.30	-26.49	577	44.84	-25.31	369	45.33	-24.55	547	46.05	-24.73
1993	681	45.71	-25.00	578	45.76	-24.21	370	45.70	-22.94	548	46.43	-23.66
1994	682	45.41	-24.51	579	45.75	-23.97	371	45.08	-21.79	549	43.81	-23.49
1995	683	45.93	-26.16	580	45.5	-23.94	372	46.07	-21.80	550	46.2	-23.74
1996	684	46.44	-24.45	581	46.38	-23.49	373	45.54	-23.68	551	45.82	-23.90
1997	685	45.54	-25.49	582	46.02	-23.94	374	45.57	-25.14	552	46.36	-24.01
1998	686	46.08	-24.81	583	44.89	-24.65	375	45.96	-23.99	553	46.5	-24.61
1999	687	45.38	-25.55	584	45.73	-23.65	376	45.46	-23.77	554	46.39	-24.85
2000	688	45.69	-25.82	585	45.45	-25.54	377	44.30	-24.74	555	45.06	-24.93
2001	689	45.29	-25.55	586	45.38	-24.56	378	45.03	-23.79	556	45.78	-25.34
2002	690	45.47	-25.58	587	44.28	-24.40	379	45.02	-23.90	557	46.27	-24.94
2003	691	44.91	-24.35	588	44.38	-24.27	380	45.27	-23.37	558	46.2	-23.84
Average			-25.24			-24.02			-23.56			-23.92
Stdev			0.13			0.14			0.15			0.12
Count		31			30			31			30	

APPENDIX 17: Analysis of foliar $\delta^{13}C$ from *Pinus pinaster* Ait. Sites GN1965a and GN1991

		%N	delta 15N	%C	delta 13C			%N	delta 15N	%C	delta 13C
1c1	lower	0.78	-1.34	47.10	-25.71	2a1	lower	0.69	-0.93	48.15	-26.24
1c1	lower	0.70	-1.60	47.37	-26.25	2a1	lower	1.02	-0.80	48.49	-27.65
1c1	lower	0.61	-1.83	47.09	-26.55	2a1	lower	1.20	-0.43	50.00	-28.73
1c1	lower	0.59	-1.77	47.41	-26.10	2a1	lower	1.31	-0.25	49.79	-29.16
1c1	lower	0.50	-0.62	46.52	-26.53	2a1	middle	0.61	-0.53	47.80	-26.24
1c1	lower	0.55	-1.75	48.28	-26.81	2a1	middle	0.71	-0.28	48.37	-26.47
1c1	middle	0.85	-0.62	46.48	-25.95	2a1	middle	0.87	-0.59	47.66	-25.52
1c1	middle	0.80	-1.10	47.44	-26.45	2a1	middle	1.11	0.00	48.90	-26.99
1c1	middle	0.76	-1.15	48.40	-26.73	2a1	middle	1.17	-0.17	47.94	-28.41
1c1	middle	0.55	-0.57	47.80	-26.38	2a1	upper	0.87	-0.33	46.37	-26.01
1c1	middle	0.52	-1.38	47.49	-27.21	2a1	upper	0.83	-0.36	46.83	-26.42
1c1	upper	0.97	-0.30	46.89	-26.72	2a1	upper	0.80	-0.65	48.08	-26.64
1c1	upper	0.77	-0.75	47.42	-26.73	2a2	lower	0.68	-1.05	47.38	-26.23
1c1	upper	0.63	-1.06	47.81	-26.85	2a2	lower	1.21	-0.95	47.01	-26.33
1c1	upper	0.53	-0.74	47.75	-27.37	2a2	lower	1.35	-0.59	49.27	-27.77
1c2	lower	0.62	-1.37	46.88	-25.69	2a2	lower	1.18	-0.26	49.37	-28.81
1c2	lower	0.63	-1.57	47.88	-26.13	2a2	lower	0.91	-0.62	48.85	-29.06
1c2	lower	0.53	-1.21	47.93	-26.98	2a2	middle	0.85	-0.57	47.15	-26.56
1c2	lower	0.46	-1.73	47.18	-26.48	2a2	middle	0.99	-0.71	48.31	-27.08
1c2	lower	0.44	-1.42	47.94	-26.91	2a2	middle	1.27	-0.47	47.54	-27.51
1c2	middle	0.88	-1.39	46.80	-26.16	2a2	middle	1.16	-0.56	47.57	-26.48
1c2	middle	0.62	-1.70	47.52	-25.68	2a2	upper	1.05	-0.72	45.35	-26.89
1c2	middle	0.52	-0.71	47.09	-26.61	2a2	upper	0.94	-0.68	47.44	-26.49
1c2	middle	0.47	-1.59	46.71	-26.64	2a2	upper	0.84	-0.40	47.17	-28.17
1c2	middle	0.49	-1.56	47.51	-26.98	2a2	upper	1.29	-0.53	47.30	-26.89
1c2	upper	0.80	-1.04	47.31	-26.05	2a3	lower	0.70	-0.85	46.30	-28.88
1c2	upper	0.64	-1.22	47.68	-25.17	2a3	lower	0.90	-0.95	46.99	-28.24
1c2	upper	0.58	-1.45	48.13	-26.28	2a3	lower	1.16	-0.72	47.39	-28.47
1c2	upper	0.47	-1.03	46.02	-26.71	2a3	lower	1.01	-0.33	48.18	-28.65
1c3	lower	0.80	-0.74	47.68	-25.08	2a3	lower	1.05	-0.11	48.53	-28.94
1c3	lower	0.75	-0.77	47.88	-25.45	2a3	lower	ns	ns	ns	ns
1c3	lower	0.61	-0.69	48.32	-26.52	2a3	middle	ns	ns	ns	ns
1c3	lower	0.45	-0.74	47.90	-26.27	2a3	middle	ns	ns	ns	ns
1c3	middle	0.78	-0.13	46.48	-25.81	2a3	middle	ns	ns	ns	ns
1c3	middle	0.63	-0.37	48.99	-25.17	2a3	middle	ns	ns	ns	ns
1c3	middle	0.52	-0.68	48.52	-25.98	2a3	upper	ns	ns	ns	ns
1c3	middle	0.51	-0.76	48.78	-26.42	2a4	lower	ns	ns	ns	ns
1c3	upper	0.79	-0.07	46.72	-25.16	2a4	lower	ns	ns	ns	ns
1c3	upper	0.67	0.00	47.58	-26.06	2a4	lower	ns	ns	ns	ns
1c3	upper	0.57	-0.33	48.34	-25.78	2a4	lower	ns	ns	ns	ns
1c3	upper	0.50	0.37	48.56	-26.52	2a4	lower	ns	ns	ns	ns
1c4	lower	0.72	0.76	47.51	-23.66	2a4	lower	ns	ns	ns	ns
1c4	lower	0.62	0.60	48.26	-24.75	2a4	lower	ns	ns	ns	ns
1c4	lower	0.60	0.56	48.41	-24.36	2a4	middle	ns	ns	ns	ns
1c4	lower	0.59	0.44	49.58	-24.79	2a4	middle	ns	ns	ns	ns
1c4	middle	0.69	0.76	47.65	-24.35	2a4	middle	ns	ns	ns	ns
1c4	middle	0.73	0.85	48.93	-23.83	2a4	middle	ns	ns	ns	ns
1c4	middle	0.79	0.60	49.93	-24.85	2a4	middle	1.09	0.52	46.39	-29.58
1c4	middle	0.55	0.37	49.49	-24.42	2a4	upper	0.64	0.24	45.60	-27.00
1c4	upper	0.76	1.27	47.79	-24.12	2a4	upper	0.75	-0.20	46.51	-27.43
1c4	upper	0.73	0.71	48.93	-25.05	2a4	upper	0.72	-0.43	46.58	-27.30
1c4	upper	0.64	0.68	49.27	-25.05	2a4	upper	0.71	0.55	45.87	-27.42
1c4	upper	0.51	0.74	46.25	-25.15	2a4	upper	0.71	0.02	45.56	-27.64

APPENDIX 18: Analysis of foliar δ^{13}C from *Pinus pinaster* Ait. Sites GN1985 and GN1965b

	Sample Title	%N	delta 15N	%C	delta 13C			%N	delta 15N	%C	delta 13C
2b5	lower	0.74	1.21	46.54	-26.12	2c1	lower	1.01	-1.28	47.77	-24.63
2b5	lower	1.09	0.96	48.18	-27.56	2c1	lower	0.87	-1.86	47.08	-24.83
2b5	lower	1.47	1.12	47.88	-27.68	2c1	lower	0.71	-2.12	48.35	-24.86
2b5	lower	1.81	1.32	46.87	-28.24	2c1	lower	0.62	-2.20	48.47	-25.25
2b5	middle	0.64	0.99	46.54	-23.52	2c1	lower	0.55	-1.55	47.54	-25.83
2b5	middle	1.04	1.09	46.57	-24.51	2c1	lower	0.54	-1.66	48.09	-26.66
2b5	middle	1.62	1.30	47.49	-27.37	2c1	middle	1.08	-1.38	48.49	-25.23
2b5	middle	1.88	1.32	48.17	-27.83	2c1	middle	0.86	-1.82	47.08	-25.91
2b5	upper	0.83	0.95	46.81	-26.39	2c1	middle	0.85	-1.49	47.42	-26.57
2b5	upper	1.24	0.79	48.06	-23.81	2c1	middle	0.77	-1.41	47.74	-26.37
2b5	upper	1.70	1.24	48.13	-25.31	2c1	middle	0.57	-1.48	48.22	-26.17
2b5	upper	2.20	1.50	48.27	-28.85	2c1	middle	0.46	-1.52	48.73	-26.44
2b6	lower	0.83	1.38	46.60	-26.37	2c1	upper	0.97	-1.54	46.06	-25.35
2b6	lower	1.18	1.01	47.42	-26.30	2c1	upper	1.03	-1.66	47.00	-26.42
2b6	lower	1.54	1.01	48.68	-25.35	2c1	upper	0.66	-1.77	48.25	-26.11
2b6	lower	1.88	0.98	48.25	-27.79	2c2	lower	0.75	-0.54	46.48	-23.52
2b6	lower	2.10	1.22	48.10	-27.98	2c2	lower	0.66	-0.70	46.73	-23.32
2b6	middle	0.78	1.36	46.23	-23.90	2c2	lower	0.59	-0.52	47.09	-24.15
2b6	middle	1.33	1.02	47.86	-26.97	2c2	lower	0.61	-0.89	48.66	-24.52
2b6	middle	1.80	1.20	48.31	-26.78	2c2	lower	0.47	-0.79	48.02	-25.15
2b6	middle	1.78	1.44	47.74	-27.35	2c2	middle	0.76	-0.31	46.15	-23.93
2b6	upper	1.05	1.29	46.45	-26.08	2c2	middle	0.66	-0.43	47.59	-24.49
2b6	upper	1.49	1.05	48.23	-25.97	2c2	middle	0.57	-0.77	47.92	-25.01
2b6	upper	1.82	1.38	47.53	-26.92	2c2	middle	0.48	-0.48	47.99	-25.23
2b7	lower	0.77	0.47	47.33	-26.46	2c2	middle	0.28	-1.41	48.57	-25.52
2b7	lower	0.83	0.18	48.23	-26.99	2c2	upper	1.06	-0.47	46.86	-23.93
2b7	lower	0.91	0.32	48.17	-28.35	2c2	upper	0.86	-0.30	47.11	-25.44
2b7	lower	1.32	0.30	48.52	-27.76	2c2	upper	0.70	-0.72	47.22	-24.95
2b7	middle	0.90	0.39	47.79	-26.40	2c2	upper	0.56	-1.08	47.66	-26.19
2b7	middle	1.19	0.46	48.51	-26.38	2c3	lower	0.60	-0.60	47.16	-25.49
2b7	middle	1.43	0.69	48.44	-26.10	2c3	lower	0.51	-0.59	48.83	-25.34
2b7	middle	1.19	0.83	48.50	-26.94	2c3	lower	0.50	-0.96	48.77	-25.89
2b7	upper	0.70	0.49	47.07	-25.53	2c3	lower	0.44	-0.76	48.77	-26.03
2b7	upper	0.92	0.78	48.33	-26.21	2c3	lower	0.39	-0.89	47.90	-26.62
2b7	upper	1.06	0.95	48.54	-26.29	2c3	middle	0.83	-0.90	46.93	-25.02
2b8	lower	0.84	-0.25	47.37	-27.43	2c3	middle	0.61	-1.16	47.91	-25.65
2b8	lower	0.96	-0.18	48.61	-27.06	2c3	middle	0.61	-1.15	48.09	-25.36
2b8	lower	1.23	0.02	49.30	-27.37	2c3	middle	0.56	-1.34	49.26	-25.99
2b8	lower	1.33	-0.13	48.90	-27.59	2c3	upper	0.78	-0.91	47.66	-24.50
2b8	middle	1.13	-0.51	47.92	-25.99	2c3	upper	0.69	-1.46	48.05	-24.40
2b8	middle	1.20	0.09	48.60	-25.61	2c3	upper	0.53	-1.28	48.03	-25.51
2b8	middle	1.22	0.21	49.07	-26.91	2c3	upper	0.55	-1.47	47.90	-24.45
2b8	upper	1.05	-0.49	47.28	-26.56	2c3	upper	0.55	-1.10	47.97	-26.65
2b8	upper	1.32	-0.07	48.81	-26.19	2c4	lower	0.63	-1.84	46.82	-26.01
2b8	upper	1.29	0.01	48.86	-26.84	2c4	lower	0.68	-2.35	46.95	-25.86
						2c4	lower	0.56	-2.88	47.24	-26.79
						2c4	lower	0.53	-2.50	47.48	-26.92
						2c4	lower	0.50	-2.57	46.80	-27.48
						2c4	middle	1.00	-1.40	47.54	-24.49
						2c4	middle	0.76	-1.96	48.20	-25.40
						2c4	middle	0.55	-1.95	48.52	-26.34
						2c4	middle	0.58	-2.16	48.29	-26.19
						2c4	upper	0.82	-1.51	47.30	-24.68
						2c4	upper	0.75	-1.94	48.08	-25.47
						2c4	upper	0.64	-1.90	48.43	-26.16
						2c4	upper	0.55	-2.02	47.82	-26.14
						2c4	upper	0.53	-1.37	47.46	-27.58

APPENDIX 19: Analysis of foliar $\delta^{13}C$ from *Pinus pinaster* Ait. Sites PJ1995 and PJ1982

		%N	delta 15N	%C	delta 13C			%N	delta 15N	%C	delta 13C
3a1	lower	0.68	-0.91	46.25	-24.30	3b1	lower	0.64	-0.50	46.88	-26.25
3a1	lower	0.71	-1.44	47.22	-25.08	3b1	lower	0.61	-0.72	47.12	-26.09
3a1	lower	0.65	-1.14	47.72	-28.64	3b1	lower	0.59	-0.88	48.36	-26.43
3a1	lower	0.58	-1.62	43.98	-33.25	3b1	lower	0.55	-0.51	49.42	-26.30
3a1	middle	0.88	-0.38	44.90	-28.69	3b1	middle	0.80	-0.29	47.28	-25.39
3a1	middle	0.80	-0.99	46.87	-27.74	3b1	middle	0.67	-0.12	48.03	-25.44
3a1	middle	0.71	-1.55	49.28	-28.44	3b1	middle	0.55	-0.53	49.02	-25.20
3a1	upper	0.87	-0.45	47.46	-24.79	3b1	middle	0.51	-0.68	49.17	-25.57
3a1	upper	0.75	-0.59	48.35	-26.69	3b1	upper	0.75	0.09	46.94	-25.94
3a2	lower	0.63	-2.16	46.99	-26.65	3b1	upper	0.60	-0.36	47.76	-26.32
3a2	lower	0.68	-1.02	48.00	-25.33	3b1	upper	0.55	-0.60	48.81	-25.68
3a2	lower	0.76	-1.73	45.98	-28.75	3b1	upper	0.56	-0.32	50.02	-26.70
3a2	lower	0.58	-1.92	45.54	-26.70	3b2	lower	0.73	0.76	48.41	-25.76
3a2	middle	0.83	-1.48	45.81	-25.88	3b2	lower	0.66	0.24	48.98	-27.14
3a2	middle	0.88	-2.33	48.07	-24.32	3b2	lower	0.73	0.03	50.45	-26.69
3a2	middle	0.73	-2.16	48.59	-26.02	3b2	lower	0.62	-0.18	50.12	-25.67
3a2	upper	0.82	-1.36	46.38	-26.02	3b2	lower	0.65	-0.49	50.87	-27.32
3a2	upper	0.85	-1.38	47.89	-25.55	3b2	middle	0.81	0.25	47.78	-26.13
3a3	lower	0.60	-2.33	48.37	-25.71	3b2	middle	0.77	-0.08	49.11	-26.09
3a3	lower	0.57	-2.16	50.04	-27.69	3b2	middle	0.62	-0.54	48.69	-26.40
3a3	middle	0.72	-1.40	46.44	-25.37	3b2	upper	0.60	2.01	46.78	-25.23
3a3	middle	0.73	-1.63	48.86	-24.75	3b2	upper	0.92	0.58	48.23	-26.66
3a3	middle	0.85	-1.81	48.75	-26.14	3b2	upper	0.95	0.53	47.95	-26.87
3a3	upper	0.69	-1.07	46.94	-25.31	3b2	upper	0.75	0.62	47.21	-27.05
3a3	upper	0.78	-1.00	48.89	-25.55	3b3	lower	0.68	-0.34	46.29	-25.87
3a4	lower	0.78	-0.29	47.78	-26.55	3b3	lower	0.81	-0.89	48.06	-26.44
3a4	lower	0.78	-1.22	48.77	-25.93	3b3	lower	0.73	-1.03	47.92	-25.49
3a4	lower	0.82	-1.59	49.12	-27.48	3b3	lower	0.71	-1.29	48.94	-25.43
3a4	lower	0.68	-1.54	50.70	-27.51	3b3	lower	0.71	-1.00	49.56	-27.08
3a4	middle	1.01	-0.30	46.70	-25.56	3b3	lower	0.64	-1.19	48.05	-26.50
3a4	middle	1.11	-0.70	48.74	-26.16	3b3	middle	0.80	-0.12	47.22	-25.66
3a4	upper	0.97	-0.25	46.95	-26.54	3b3	middle	0.81	-0.41	47.83	-25.77
3a4	upper	1.02	-0.64	47.55	-27.16	3b3	middle	0.65	-0.91	47.52	-25.99
						3b3	middle	0.67	-1.12	48.28	-25.02
						3b3	upper	0.53	1.21	45.71	-24.43
						3b3	upper	0.87	-0.18	47.01	-25.26
						3b3	upper	0.74	-0.18	47.77	-25.70
						3b3	upper	0.70	-0.41	48.43	-25.67
						3b3	upper	ns	ns	ns	ns
						3b4	lower	ns	ns	ns	ns
						3b4	lower	0.74	-0.94	48.76	-25.45
						3b4	lower	0.66	-1.18	48.55	-25.68
						3b4	lower	0.67	-1.51	49.82	-25.42
						3b4	lower	0.63	-1.26	51.04	-25.62
						3b4	middle	0.97	-0.54	48.02	-25.12
						3b4	middle	0.73	-1.24	48.57	-25.12
						3b4	middle	0.64	-1.09	48.35	-25.38
						3b4	middle	0.56	-0.92	47.27	-25.26
						3b4	upper	0.73	-0.09	46.54	-25.65
						3b4	upper	0.63	-0.81	47.96	-25.84

APPENDIX 20: Analysis of foliar $\delta^{13}C$ from *Pinus pinaster* Ait. Site PJ1971

		%N	delta 15N	%C	delta 13C
3c1	lower	0.71	-0.72	46.66	-27.70
3c1	lower	0.71	-1.37	48.51	-27.54
3c1	lower	0.77	-1.85	48.33	-26.93
3c1	lower	0.67	-1.75	48.91	-26.80
3c1	lower	0.64	-1.83	48.74	-26.89
3c1	middle	0.79	-1.13	46.97	-27.09
3c1	middle	0.78	-1.45	48.62	-26.43
3c1	middle	0.68	-1.64	47.91	-26.69
3c1	middle	0.65	-1.59	48.23	-25.95
3c1	upper	0.87	-0.67	46.58	-27.01
3c1	upper	0.75	-1.55	48.40	-26.09
3c1	upper	0.78	-1.02	48.20	-26.84
3c1	upper	0.71	-1.21	47.99	-27.06
3c2	lower	0.61	-0.99	47.05	-25.63
3c2	lower	0.69	-1.04	48.21	-25.65
3c2	lower	0.69	-1.40	48.19	-26.14
3c2	lower	0.66	-1.56	48.78	-25.76
3c2	lower	0.72	-1.65	49.35	-26.10
3c2	lower	0.64	-1.49	48.66	-26.04
3c2	middle	0.73	-0.94	46.85	-25.52
3c2	middle	0.76	-1.00	48.03	-23.64
3c2	middle	0.75	-1.41	49.13	-25.08
3c2	middle	0.66	-1.38	49.53	-24.75
3c2	upper	0.78	-0.32	47.12	-26.23
3c2	upper	0.68	-0.82	48.89	-25.36
3c2	upper	0.66	-1.27	48.35	-25.71
3c3	lower	0.70	-1.56	47.49	-25.91
3c3	lower	0.75	-2.17	48.24	-26.09
3c3	lower	0.73	-2.39	47.59	-25.76
3c3	lower	0.67	-1.61	47.80	-25.53
3c3	middle	0.83	-1.58	47.49	-25.44
3c3	middle	0.93	-1.74	47.72	-24.64
3c3	middle	0.78	-2.32	48.08	-24.41
3c3	middle	0.77	-2.07	49.13	-24.42
3c3	upper	0.86	-0.97	47.31	-25.85
3c3	upper	0.73	-1.61	48.65	-24.95
3c3	upper	0.76	-1.47	49.28	-24.93
3c3	upper	0.61	-1.16	48.30	-26.09
3c4	lower	ns	ns	ns	ns
3c4	lower	0.73	-1.78	47.66	-24.64
3c4	lower	0.68	-1.96	47.57	-25.28
3c4	lower	0.57	-1.43	48.04	-26.56
3c4	lower	0.60	-1.92	48.06	-26.61
3c4	lower	0.59	-1.45	48.70	-26.44
3c4	lower	0.60	-1.22	47.59	-26.45
3c4	middle	0.79	-1.06	47.06	-24.39
3c4	middle	0.79	-1.25	48.05	-24.80
3c4	middle	0.70	-1.61	47.94	-24.99
3c4	middle	0.69	-1.08	49.49	-25.49
3c4	middle	0.59	-1.33	48.59	-26.14
3c4	middle	0.57	-1.02	49.43	-26.55
3c4	middle	0.51	-0.54	49.08	-26.38
3c4	upper	0.83	-0.66	46.53	-25.10
3c4	upper	0.78	-0.88	49.19	-24.15
3c4	upper	0.70	-0.96	48.66	-25.27
3c4	upper	0.56	-0.87	49.13	-26.25

APPENDIX: 21: Sampling height and branch length attributes for *Pinus pinaster* foliar samples obtained for $\delta^{13}C$ analysis.

		GN1991	GN1985	GN1965a	GN1965b	PJ1995	PJ1982	PJ1971
Mean lower sample height (m)	vertical height	3.16 (+/-0.25)	9.30 (+/-0.61)	14.34 (+/-0.81)	12.21 (+/-0.84)	1.41 (+/-0.14)	5.22 (+/-0.31)	9.44 (+/-1.5)
	stem length	1.85 (+/-0.19	2.40 (+/- 0.28)	4.46 (+/-0.14)	4.05 (+/-0.52)	2.02 (+/-0.23)	3.34 (+/-0.25)	3.60 (+/-0.18)
Mean middle sample height (m)	vertical height	6.24 (+/-0.42	11.66 (+/-0.69)	17.35 (+/-0.53)	16.75 (+/-0.56)	3.73 (+/-0.28)	9.48 (+/-0.45)	11.81 (+/-0.93)
	stem length	1.48 (+/-0.03	2.36 (+/-0.26)	3.45 (+/-0.50)	4.98 (+/-0.50)	2.1 (+/-0.31)	4.05 (+/-0.30)	4.57 (+/-0.78)
Mean upper sample height (m)	vertical height	8.56 (+/-0.43)	13.43 (+/-0.57)	20.08 (+/-0.63)	18.74 (+/-0.66)	6.23 (+/-0.34)	13.96 (+/-0.26)	15.71 (+/-0.59)
	stem length	1.07 (+/-0.26)	1.60 (+/-0.35)	2.97 (+/-0.25)	3.50 (+/-0.34)	1.33 (+/-0.23)	2.21 (+/-0.21)	3.22 (+/-0.41)
Mean sum of branch length and sample height (m)	Lower	5.01 (+/-0.17)	11.71 (+/-0.55)	18.80 (+/-0.79)	16.27 (+/-1.18)	3.44 (+/-0.32)	8.57 (+/-0.53)	13.04 (+/-1.67)
	Middle	7.73 (+/-0.43)	14.02 (+/-0.57)	20.81 (+/-0.29)	21.73 (+/-0.33)	5.83 (+/-0.23)	13.54 (+/-0.49)	16.38 (+/-1.21)
	Upper	9.63 (+/-0.33)	15.04 (+/-0.29)	23.05 (+/-0.61)	22.24 (+/-0.48)	7.55 (+/-0.16)	16.17 (+/-0.45)	18.93 (+/-0.80)
Mean leaf age retained	Lower	5.25 (+/-0.63)	4.25 (+/-0.25)	4.75 (+/-0.48)	5.25 (+/-0.25)	3.5 (+/-0.50)	5 .0 (+/-0.41)	5.5 (+/-0.65)
	Middle	4.25 (+/-0.25)	3.75 (+/-0.25)	4.5 (+/-0.29)	4.75 (+/-0.48)	2.75 (+/-0.25)	3.75 (+/-0.25)	4.75 (+/-0.75)
	Upper	2.75 (+/-0.85)	3.25 (+/-0.25)	4.0 (+/-0.0)	4.25 (+/-0.48)	2.0 (+/-0.0)	3.75 (+/-0.63)	3.75 (+/-0.25)

Edith Cowan University School of Natural Sciences JOONDALUP, Western Australia	LOG OF BORING SB1: Site GN1991

Honours Research Project

By Lindsay Bourke

Date Started	: 28 April 2004	Datum	: WGS84
Date Completed	: 28 April 2004	Northing Coord.	: 6489701
Core Diameter	: 19 mm	Easting Coord.	: 397875
Drilling Method	: Percussive constant core	Checked by	: Lindsay Bourke
Drilling Company	: J&S Drilling	Logged by	: Kel Baldock

Depth in Meters	Surf. Elev. 60	USCS	GRAPHIC	DESCRIPTION	SAMPLE DEPTHS	Water Level
0	60	SP		SAND, Well Graded, white-grey, medium grained, dry	0.0 to 0.6 m Sample 1A, and 1B	
1	59				0.6 to 1.8 m Sample 2A, 2B, and 2C	
2	58	MS		HARDPAN/HUMUS layer Graduating to SAND, mottled, brown/discoloured from 2.0 to 2.4 mbgl	1.8 to 3.0 m Sample 3A, 3B, and 3C	
		LS		LIMESTONE/SANDSTONE		
3	57	SW		SAND, Poorly Graded, mottling present, medium grained, dry.	3.0 to 3.6 m Sample 4A, 4B, and 4C	
				EOH @ 3.6 mbgl		
4	56					
5	55					
6	54					
7	53					
8	52					
9	51					
10	50					
11	49					
12	48					
13						

Edith Cowan University School of Natural Sciences JOONDALUP, Western Australia	LOG OF BORING SB2: Site GN1985

Honours Research Project By Lindsay Bourke				
	Date Started	: 28 April 2004	Datum	: WGS84
	Date Completed	: 28 April 2004	Northing Coord.	: 6489881
	Core Diameter	: 19 mm	Easting Coord.	: 396870
	Drilling Method	: Percussive constant core	Checked by	: Lindsay Bourke
	Drilling Company	: J&S Drilling	Logged by	: Kel Baldock

Depth in Meters	Surf. Elev. 60	USCS	GRAPHIC	DESCRIPTION	SAMPLE DEPTHS	Water Level
0	60	SP		SAND, Well Graded, white-grey, medium grained, dry, light organics present.	0.0 to 0.6 m Sample 1A, and 1B	
1	59				0.6 to 1.2 m Sample 2A, 2B, and 2C	
2	58	SW		SAND, Well Graded, grey, graduating to SAND, brown becoming firm hardpan layer. Change at 2.4 mbgl to: SAND, brown, mottled with pale layers	1.2 to 2.4 m Sample 3A, 3B, and 3C	
3	57	MS		HARDPAN/HUMUS layer, dark-brown	2.4 to 3.6 m Sample 4A, 4B, and 4C	▼
				EOH @ 3.6 mbgl		
4	56					
5	55					
6	54					
7	53					
8	52					
9	51					
10	50					
11	49					
12	48					
13						

Edith Cowan University School of Natural Sciences JOONDALUP, Western Australia	LOG OF BORING SB3: Site GN1965a

Honours Research Project By Lindsay Bourke				
	Date Started	: 28 April 2004	Datum	: WGS84
	Date Completed	: 28 April 2004	Northing Coord.	: 6490601
	Core Diameter	: 19 mm	Easting Coord.	: 399166
	Drilling Method	: Percussive constant core	Checked by	: Lindsay Bourke
	Drilling Company	: J&S Drilling	Logged by	: Kel Baldock

Depth in Meters	Surf. Elev. 60	USCS	GRAPHIC	DESCRIPTION	SAMPLE DEPTHS	Water Level
0	60	SP		Organic horizon top 100 mm		
		SW		SAND, grey, medium grained,dry, with organic material.		
1	59			SAND, grey, graduating to SAND, white, mottled,	0.0 to 1.2 m Sample 1A, 1B, and 1C	
2	58				1.2 to 2.4 m Sample 2A, 2B, and 2C	
		MS		HARDPAN, dark-brown caprock, calcrete layer, increasing density with depth, swampy odour		▼
3	57	Pt		SAND, grey, high organic component, peat-like material present,very moist.	2.4 to 3.6 m Sample 3A, 3B, and 3C	
4	56				3.6 to 4.2 m Sample 4A, 4B, and 4C	
				EOH @ 4.2 mbgl		
5	55					
6	54					
7	53					
8	52					
9	51					
10	50					
11	49					
12	48					
13						

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LOG OF BORING SB4: Site GN1965b

Honours Research Project

By Lindsay Bourke

Date Started	: 28 April 2004	Datum	: WGS84
Date Completed	: 28 April 2004	Northing Coord.	: 6489813
Core Diameter	: 19 mm	Easting Coord.	: 397764
Drilling Method	: Percussive constant core	Checked by	: Lindsay Bourke
Drilling Company	: J&S Drilling	Logged by	: Kel Baldock

Depth in Meters	Surf. Elev. 60	USCS	GRAPHIC	DESCRIPTION	SAMPLE DEPTHS	Water Level
0	60	SP		SAND, Well Graded, white-grey, medium grained, dry, light organics present in upper 0.2 m	0.0 to 0.6 m Sample 1A, and 1B	
1	59	SW		SAND, Well Graded, grey, dry,	0.6 to 1.2 m Sample 2A, 2B, and 2C	
2	58	SC		SAND, grey, medium grained, Aeolean clay (talk-like) evident throughout profile, dry,	1.2 to 2.4 m Sample 3A, 3B, and 3C	
		MS		SAND, Poorly Graded, grey, graduating quickly to brown HARDPAN		
3	57			EOH @ 2.8 mbgl		
4	56					
5	55					
6	54					
7	53					
8	52					
9	51					
10	50					
11	49					
12	48					
13						

Edith Cowan University School of Natural Sciences JOONDALUP, Western Australia	LOG OF BORING SB5: Site PJ1995

Honours Research Project By Lindsay Bourke	Date Started : 27 April 2004 Date Completed : 29 April 2004 Core Diameter : 19 mm Drilling Method : Percussive constant core Drilling Company : J&S Drilling	Datum : WGS84 Northing Coord. : 6506080 Easting Coord. : 382601 Checked by : Lindsay Bourke Logged by : Kel Baldock

Depth in Meters	Surf. Elev. 62	USCS	GRAPHIC	DESCRIPTION	SAMPLE DEPTHS	Water Level
0	62	SP		Organic horizon top 100 mm with SAND, white medium grained,dry.	0.0 to 0.6 m Sample 1A, 1B, and 1C	
1	61			SAND, Poorly Graded, pale-yellow, medium grained,dry.	0.6 to 1.2 m Sample 2A, 2B, and 2C	
		SW		SAND, Well Graded, pale-yellow, medium grained, dry.		
2	60				1.2 to 2.4 m Sample 3A, 2B, and 2C	
3	59				2.4 to 3.6 m Sample 4A, 4B, and 4C	
4	58				3.6 to 4.8 m Sample 5A, 5B and 5C	
5	57				4.8 to 6.0 m Sample 6A, 6B, and 6C	
6	56			Increasing moisture with depth after 6.0 mbgl	6.0 to 7.2 m Sample 7A, 7B, and 7C	
7	55			Change at 6.6 mbgl to: SAND, Well Graded, deep yellowish brown, medium grained.	7.2 to 8.4 m Sample 8A, 8B, and 8C	
8	54			Change at 7.55 m to: SAND, Well Graded, pale yellowish brown, medium grained.	8.4 to 9.6 m Sample 9A, and 9B	
		LS		SANDSTONE, softly cemented horizon		
9	53	SW		SAND, Well Graded, yellowish brown, medium grained, slightly moist.	9.6 to 10.8 m Sample 10A, and 10B	
10	52				10.8 to 11.4 m Sample 11A, and 11B	
11	51					
12	50			EOH @ 12.0 mbgl		
13						

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LOG OF BORING SB6: Site PJ1982

Honours Research Project

By Lindsay Bourke

Date Started	: 27 April 2004	Datum	: WGS84
Date Completed	: 27 April 2004	Northing Coord.	: 6506456
Core Diameter	: 19 mm	Easting Coord.	: 382172
Drilling Method	: Percussive constant core	Checked by	: Lindsay Bourke
Drilling Company	: J&S Drilling	Logged by	: Kel Baldock

Depth in Meters	Surf. Elev. 62	USCS	GRAPHIC	DESCRIPTION	SAMPLE DEPTHS	Water Level
0	62	SP		Organic horizon top 100 mm with SAND, white medium grained,dry.	0.0 to 0.6 m Sample 1A, 1B, and 1C	
		SW		SAND, Poorly Graded, pale-yellow graduating to yellow, medium grained, dry.		
1	61				0.6 to 1.2 m Sample 2A, 2B, and 2C	
		SW		SAND, Well Graded, yellowish brown, medium grained, dry.		
2	60				1.2 to 2.4 m Sample 3A, 2B, and 2C	
3	59				2.4 to 3.6 m Sample 4A, 4B, and 4C	
4	58			Increasing moisture with depth after 4.2 mbgl	3.6 to 4.8 m Sample 5A, 5B and 5C	
5	57				4.8 to 6.0 m Sample 6A, 6B, and 6C	
6	56				6.0 to 7.2 m Sample 7A, 7B, and 7C	
				Change at 6.8 mbgl to: SAND, Well Graded, pale-yellowish, medium grained.		
7	55				7.2 to 8.4 m Sample 8A, 8B, and 8C	
				Change at 7.2m to: SAND, Well Graded, yellowish brown, medium grained, slightly moist.		
8	54				8.4 to 9.6 m Sample 9A, 9B, and 9C	
9	53				9.6 to 10.8 m Sample 10A, 10B, and 10B	
10	52					
11	51			EOH @ 10.8 mbgl		
12	50					
13						

Edith Cowan University School of Natural Sciences JOONDALUP, Western Australia	LOG OF BORING SB7: Site PJ1971

Honours Research Project By Lindsay Bourke				
	Date Started	: 29 April 2004	Datum	: WGS84
	Date Completed	: 29 April 2004	Northing Coord.	: 6505763
	Core Diameter	: 19 mm	Easting Coord.	: 382585
	Drilling Method	: Percussive constant core	Checked by	: Lindsay Bourke
	Drilling Company	: J&S Drilling	Logged by	: Kel Baldock

Depth in Meters	Surf. Elev. 62	USCS	GRAPHIC	DESCRIPTION	SAMPLE DEPTHS	Water Level
0	62	SP		Organic horizon top 50 mm with SAND, white medium grained,dry.	0.0 to 1.2 m Sample 1A, 1B, and 1C	
1	61	SW		SAND, Well Graded, pale-yellow graduating to yellow, medium grained, dry.		
				SAND, Well Graded, yellowish brown, medium grained, dry.		
2	60			Slight increase in moisture after 2.0 mbgl	1.2 to 2.4 m Sample 2A, 2B, and 2C	
3	59				2.4 to 3.6 m Sample 3A, and 2B	
4	58			Increasing moisture with depth after 4.8 mbgl	3.6 to 4.8 m Sample 4A, 4B, and 4C	
5	57	SW			4.8 to 6.0 m Sample 5A, 5B and 5C	
6	56			Noticable increase in moisture after 6.0 mbgl	6.0 to 7.2 m Sample 6A,and 6B	
7	55				7.2 to 8.4 m Sample 7A, 7B, and 7C	
8	54				8.4 to 9.6 m Sample 8A, and 8B	
				SAND, Well Graded, pale-yellow, medium grained, moist		
9	53	SW				
10	52			EOH @ 9.2 mbgl		
11	51					
12	50					
13						

APPENDIX 29: $\delta^{13}C$ and nitrogen concentrations for foliar samples

Interannual δ13C signature of foliar material

Leaves were retained on the sampled *Pinus pinaster* Ait. trees from two to seven years, with the average being 4 years. In all cases the lower strata retained leaves for the longest period and leaf persistence was positively related to tree age (i.e. oldest trees retained leaves the longest). On average the leaf $\delta^{13}C$ signatures agreed with the theoretical model (Farquhar *et al.*, 1982) with regards to light interception, as the $\delta^{13}C$ of the lower strata at most sites was most negative. With the exception of site PJ1982 the $\delta^{13}C$ signature of the oldest foliage was most negative, irrespective of location within the canopy, and progressively became more positive in successive years. This trend was similar to that observed by Warren and Adams (2000b).

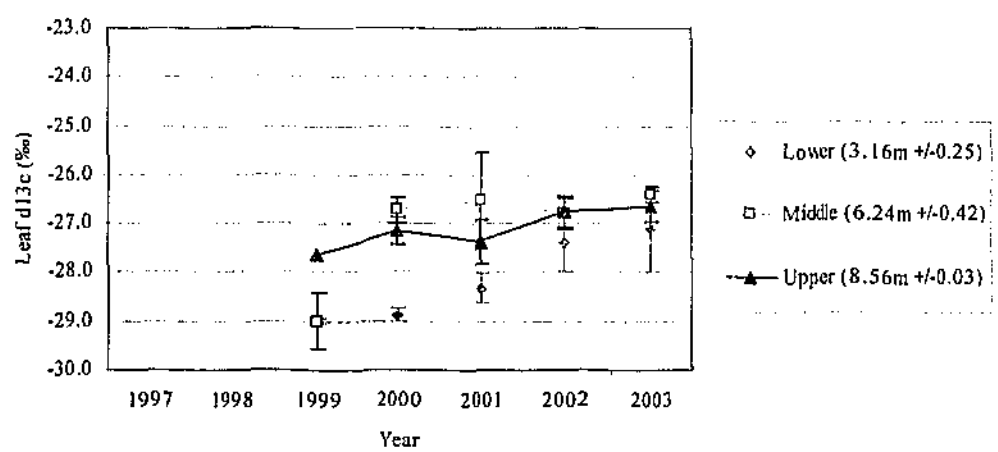

Figure 6.1 Line graph representing the mean and standard error of the $\delta^{13}C$ signature of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site GN1991. Sample heights above ground level are denoted in brackets.

At site GN1991 (Figure 6.1), the mean $\delta^{13}C$ signature of the lower strata was consistently more negative that all other strata and commenced at -29.0‰ in 1999, increasing to -27.1‰ in 2003. The middle strata also commenced at -29.0‰ in 1999 and increased by Δ2.3‰ in 2000, after this period $\delta^{13}C$ increased slightly to -26.4‰ in 2003. The $\delta^{13}C$ signature of the upper strata was the most positive in 1999 and commenced at -27.6‰, increasing in a similar pattern to the lower strata where it reached a value of -26.6‰ in 2003.

At site PJ1995 (Figure 6.2), the mean $\delta^{13}C$ trends of the lower strata were relatively consistent with site GN1991 and with exception of 2003, were the most negative. Commencing in 2000, the $\delta^{13}C$ of the lower strata was -29.1‰, increasing about Δ1.0‰ per year reaching -25.8‰ in 2003. Three foliage whorls were sampled for the middle strata and $\delta^{13}C$ was -26.9‰ in 2001, increasing to -25.7‰ in 2002, and then decreasing to -26.4 in 2003. The upper stratum $\delta^{13}C$ was -26.2‰ in 2002, increasing moderately to 25.7‰ in 2003.

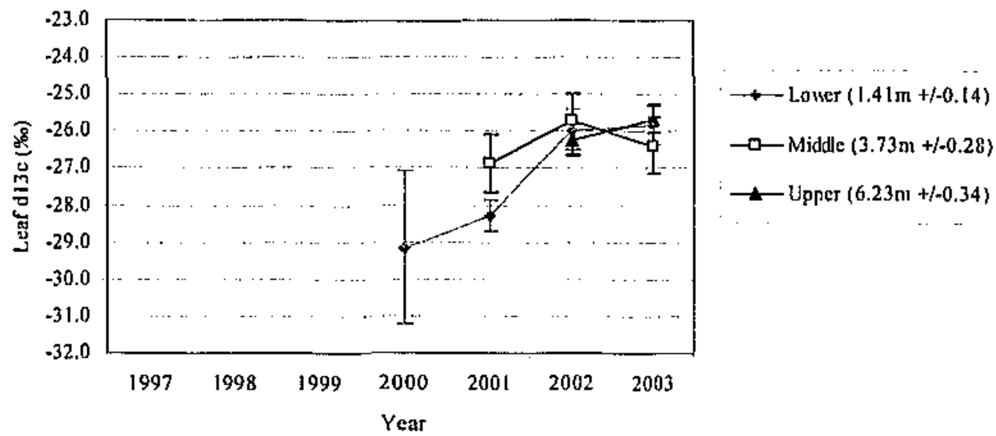

Figure 6.2: Line graph representing the mean and standard error of the $\delta^{13}C$ signature of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site PJ1995. Sample heights above ground level are denoted in brackets.

At site GN1985 (Figure 6.3), with the exception of 2000, the lower strata was consistently more negative than all other strata. In 1999 the mean $\delta^{13}C$ was -28‰ and increased in consecutive years to -26.6‰ in 2003. The $\delta^{13}C$ trends of the middle strata were similar to those of the lower strata however remained more positive. In 2000 $\delta^{13}C$ was -27.4‰ and increased about Δ1‰ per year to -24.9‰ in 2003. In 2000 the mean $\delta^{13}C$ was the most negative at -28.8‰, increasing over consecutive years to -25.5‰ in 2002 then decreased moderately to -26.1‰ in 2003.

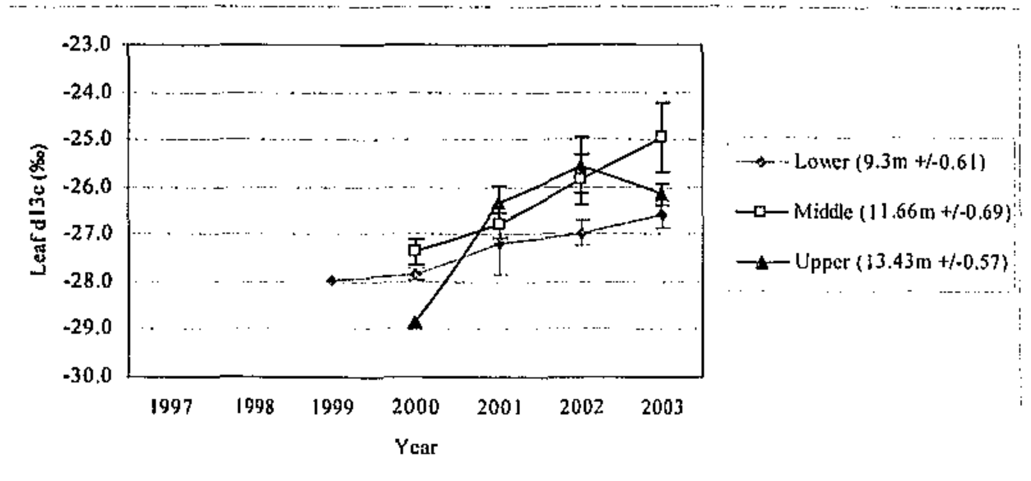

Figure 6.3: Line graph representing the mean and standard error of the $\delta^{13}C$ signature of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site GN1985. Sample heights above ground level are denoted in brackets.

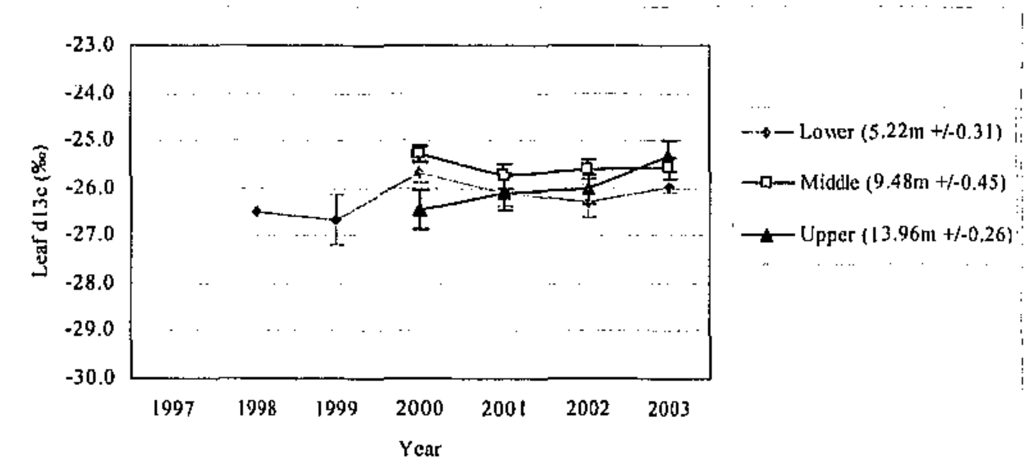

Figure 6.4: Line graph representing the mean and standard error of the $\delta^{13}C$ signature of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site PJ1982. Sample heights above ground level are denoted in brackets.

At site PJ1982 (Figure 6.4), the lower strata mean $\delta^{13}C$ was -26.5‰ in 1999, increasing about Δ0.1‰ per year to -26‰ in 2003. The $\delta^{13}C$ signature for the middle strata increased commenced at -25.8‰ in 2000 and decreased marginally over four years to -25.6‰ in 2003. The $\delta^{13}C$ trend of the upper strata was more characteristic of the trends observed at other sites and commenced at -26.5‰ in 2000 and increased moderately in successive years to -25.3‰ in 2003.

At site GN1965a (Figure 6.5), there were relatively insignificant differences in the mean $\delta^{13}C$ signatures between all strata over time. The lower strata $\delta^{13}C$ values ranged from -26.8‰ in 1998 increasing to -25.0‰ in 2003. The middle strata mean $\delta^{13}C$ values ranged from -27.1‰ in 1999, increasing to -25.3‰ in 2002, and then decreasing moderately to -25.6‰ in 2003. The upper strata mean $\delta^{13}C$ was -26.4‰ in 2000, increasing over successive years to -25.5‰ in 2003.

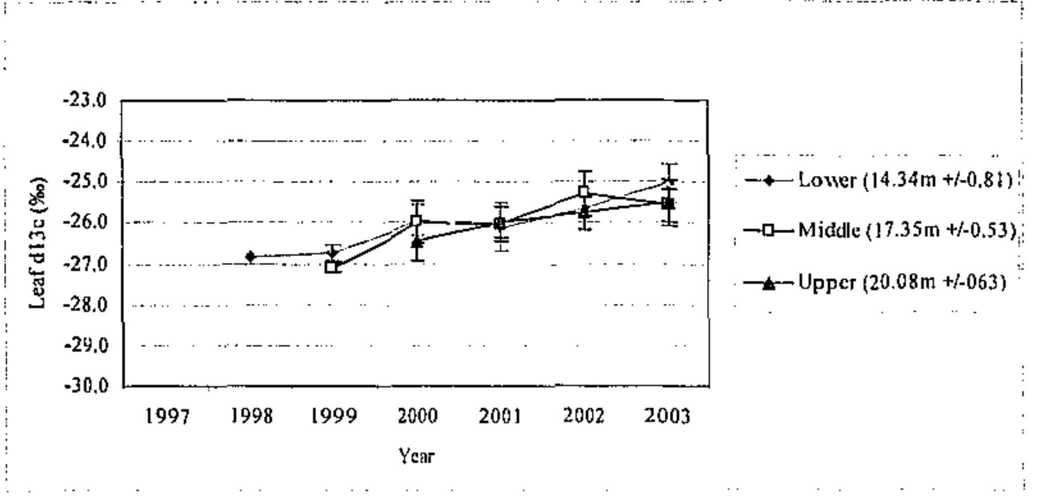

Figure 6.5: Line graph representing the mean and standard error of the $\delta^{13}C$ signature of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site GN1965a. Sample heights above ground level are denoted in brackets.

At site GN1965b (Figure 6.6), the mean $\delta^{13}C$ values of all strata increased over time. Commencing in 1998 the mean $\delta^{13}C$ of the lower strata was -26.7‰, increasing to gradually to -24.9‰ in 2003. The mean $\delta^{13}C$ of the middle strata commenced at -26.4‰ and was moderately more positive than the lower strata from 1998 to 1999. $\delta^{13}C$ decreased moderately to -25.9‰ in 2000, then increasing again over consecutive years to -24.7‰ in 2003. The upper strata commenced at -27.1‰ in 1999, increasing to -25.6‰ in 2000, then generally increased over consecutive years to -24.6‰ in 2003.

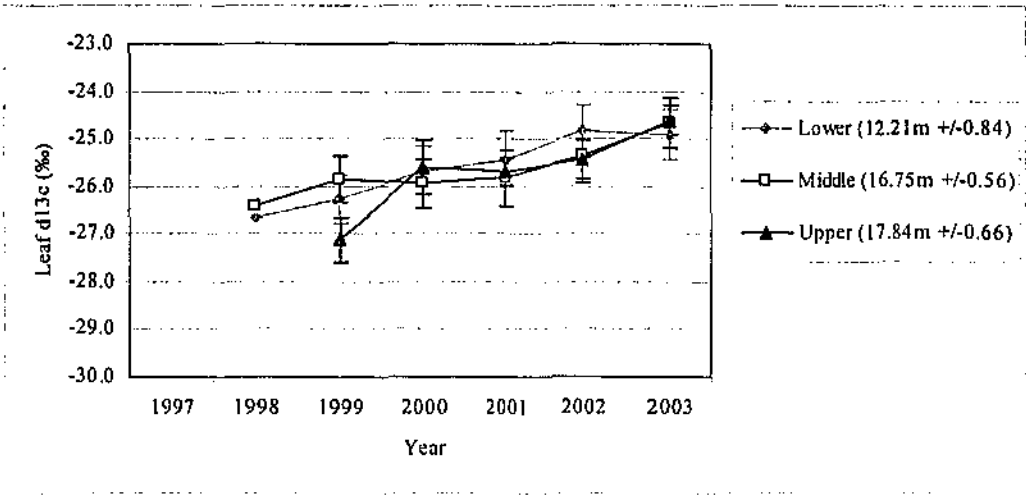

Figure 6.6: Line graph representing the mean and standard error of the $\delta^{13}C$ signature of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site GN1965b. Sample heights above ground level are denoted in brackets.

Site PJ1971 (Figure 6.7) retained on average the highest number of leaf whorls representing a $\delta^{13}C$ record from 1997 to 2003 for the lower and middle canopy strata. The general trend for the lower strata was consistent with the other sites, being more negative than the other strata over time. Commencing in 1997 the mean $\delta^{13}C$ values for the lower strata was -26.4‰, increasing to -26‰ in 2002, decreasing slightly to -26.4‰ in 2003. The mean $\delta^{13}C$ trends of the middle strata were similar to the lower strata. In 1997 the mean $\delta^{13}C$ was -26.4‰, decreasing moderately to -26.5‰ in 1998, increasing over the next two years to -25.2‰ in 2000. The mean $\delta^{13}C$ decreased to -25.3‰ in 2001, increasing to -24.9‰ in 2002 then decreasing to -25.6‰ in 2003. In 2000 the mean $\delta^{13}C$ of the upper strata was -26.5‰, increasing to -25.1‰ in 2002, then decreasing to -26.0‰ in 2003.

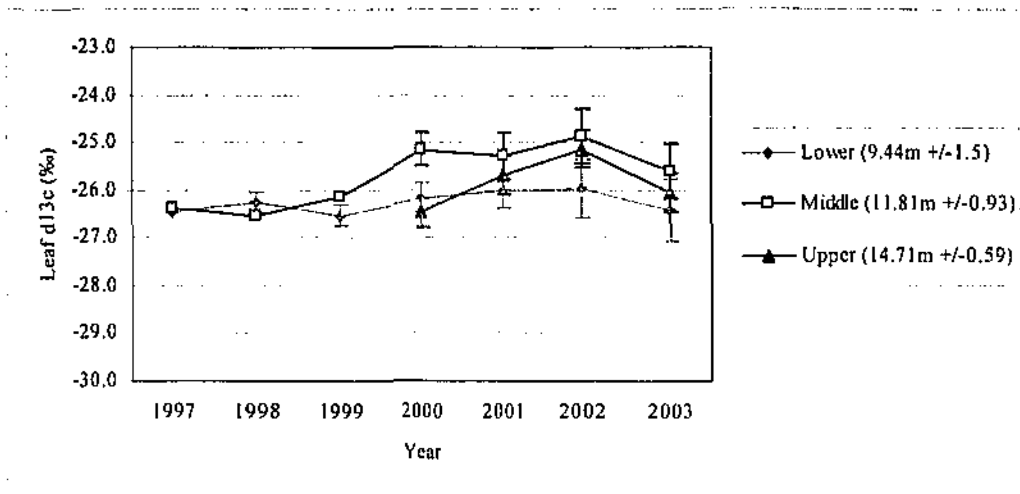

Figure 6.7: Line graph representing the mean and standard error of the $\delta^{13}C$ signature of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site PJ1971. Sample heights above ground level are denoted in brackets.

Correlation between foliar δ13C and branch length

Warren and Adams (2000b) found a significant relationship between hydraulic conductance, branch length and the $\delta^{13}C$ signature stored in foliage of *Pinus pinaster* Ait. located on a low rainfall region in the Southwest of Western Australia. Consequently the influence of these parameters upon $\delta^{13}C$ was tested. The $\delta^{13}C$ signature for the current growing season foliage (C) was regressed against branch length, branch height and the total pathway length which was estimated by summing branch length and branch height (Table 6.1). In all cases there was a significant correlation, however the various branch characteristics explained less than 13% of the $\delta^{13}C$ signature.

Table 6.1: Correlation between the branch length, branch height and total pathway length (sum of branch length and branch height) and the foliage $\delta^{13}C$ signature for the current year (C).

Current leaf $\delta^{13}C$	n	Adjusted r^2	*P*	F	Coefficient	
					Beta	Constant
Branch length	77	0.10	0.003	9.55	-26.508	0.272
Branch height	77	0.11	0.002	10.29	-26.466	0.068
Total pathway length	77	0.13	0.001	12.77	-26.645	0.066

The $\delta^{13}C$ signature of the current year's foliage represents the carbon fixed since initial leaf extension, thus the $\delta^{13}C$ signature of the preceding year's foliage represents the photosynthetic conditions present during leaf emergence and/or mobilised reserves of assimilated carbon over time (Waring & Silvester, 1997). With this in mind the long-term foliage $\delta^{13}C$ signatures for each stratum were averaged and regressed against branch length, branch height, and the total pathway length (Table 6.2). The correlation between branch characteristics and the long-term $\delta^{13}C$ (C to C+6) was stronger than the current year's foliage $\delta^{13}C$ signature and total branch length explained up to 26% of the mean leaf $\delta^{13}C$.

Table 6.2: Correlation between the branch length, branch height and total pathway length (sum of branch length and branch height) and the mean foliage $\delta^{13}C$ signature from 1997 to 2003 (C to C+6).

Mean leaf $\delta^{13}C$	n	Adjusted r^2	*P*	F	Coefficients	
					Beta	Constant
Branch length	80	0.22	0.00	22.233	-27.205	0.351
Branch height	80	0.21	0.00	20.689	-27.076	0.082
Total pathway length	80	0.26	0.00	27.300	-27.308	0.081

Analysis of nitrogen in foliar material

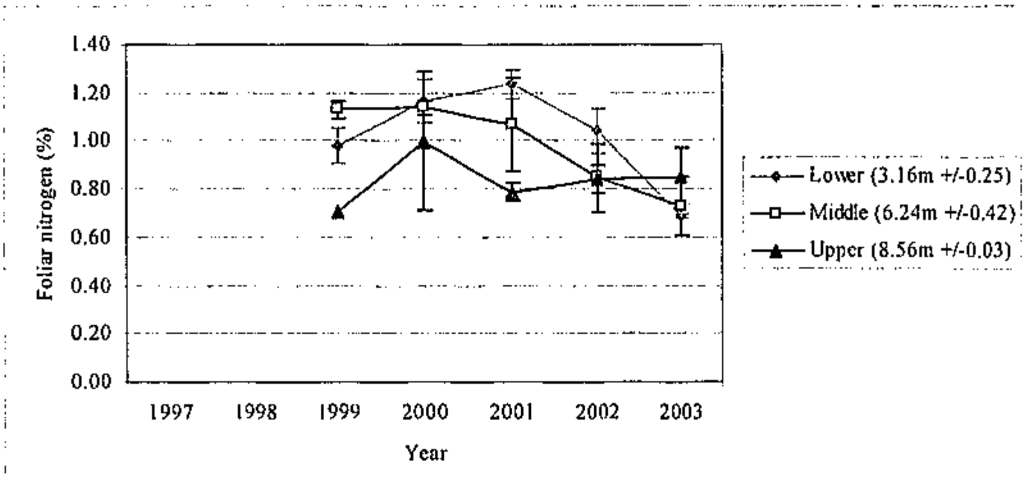

Figure 6.9: Line graph representing the mean and standard error of the percentage nitrogen of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site GN1991. Sample heights above ground level are denoted in brackets.

At site GN1991 (Figure 6.9) the mean nitrogen concentrations of the lower strata commenced at 1% in 1999, increasing to 1.2% in 2001 then decreasing over consecutive years to 0.7% in 2003. The trends were similar for the middle strata foliage nitrogen concentrations commencing at 1.1% in 1999, decreasing over consecutive years to 0.7% in 2003. The mean upper strata nitrogen concentration was 0.7% in 1999, increasing to 1% in 2000, decreasing to 0.8% in 2001 then increasing moderately to 0.85% in 2003.

The mean nitrogen concentration in 2000 for the lower strata at site PJ1995 (Figure 6.10) was 0.6%, increasing moderately to 0.74% in 2001, and decreasing to 0.67% in 2003. The middle strata mean nitrogen concentration in 2001 was 0.8%, increasing to 0.88% in 2002 then 0.86% in 2003. The upper strata mean nitrogen concentration in 2002 and 2003 remained relatively constant at 0.8%.

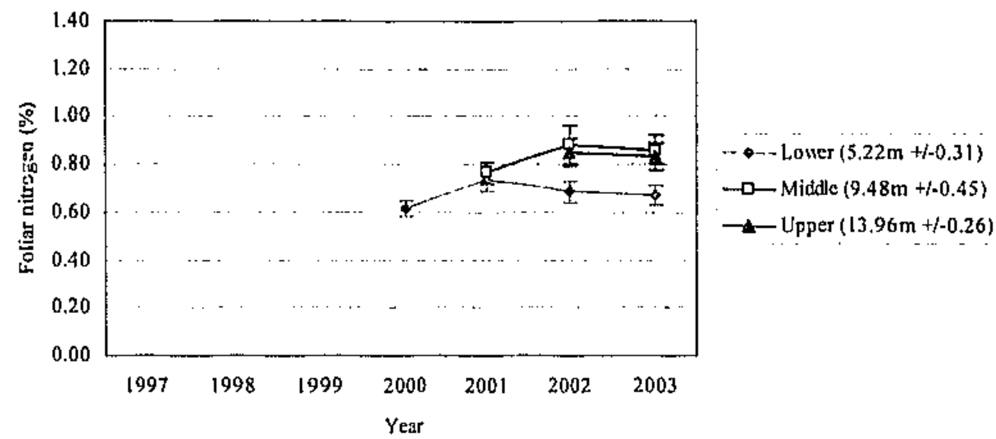

Figure 6.10: Line graph representing the mean and standard error of the percentage nitrogen of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site PJ1995. Sample heights above ground level are denoted in brackets.

At site GN1985 (Figure 6.11), the mean foliar nitrogen concentrations of all strata in 1999 and 2000 were relatively elevated. In 1999 the mean nitrogen concentration of the lower strata was 2.1%, decreasing over consecutive years to 0.8% in 2003. The mean nitrogen concentration of the middle strata commenced at 1.6% and decreased in a linear fashion to 0.9% in 2003. The mean nitrogen concentration trends for the upper strata commenced at 2.2% in 2000 and declined in a similar manner to the other strata to 0.9% in 2003.

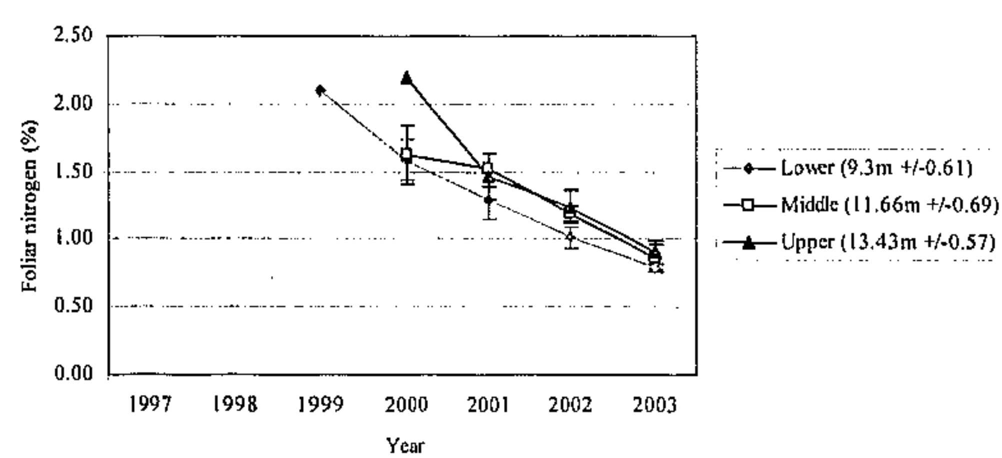

Figure 6.11: Line graph representing the mean and standard error of the percentage nitrogen of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site GN1985. Sample heights above ground level are denoted in brackets.

The mean foliar nitrogen concentrations at site PJ1982 (Figure 6.12) ranged from about 0.6% to 0.8%. In 1998 the mean nitrogen concentration for the lower strata was 0.6%, remaining relatively stable over subsequent years reaching a maximum of

0.71% in 2002 then declining to 0.68% in 2003.The middle strata N was 0.6% in 2000, increasing over consecutive years to 0.8% in 2003. The upper strata commenced at 0.7% in 2000, increasing to 0.75% in 2001 and 2002, decreasing to 0.65% in 2003.

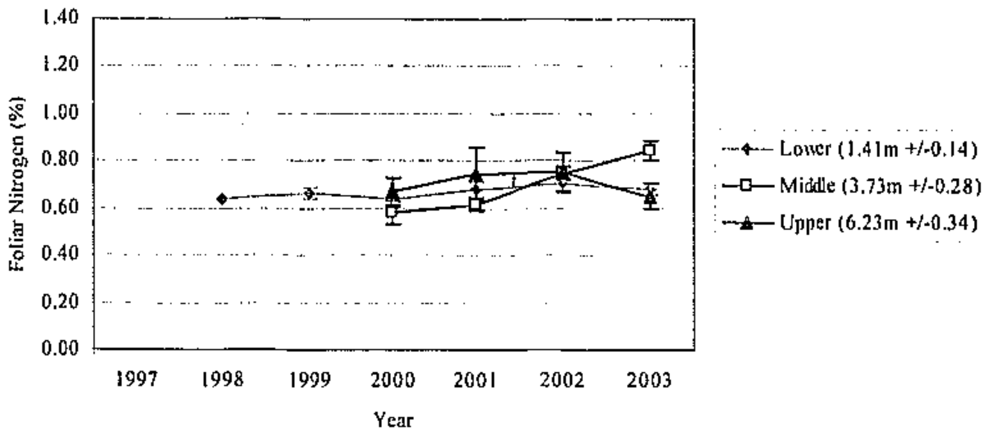

Figure 6.12: Line graph representing the mean and standard error of the percentage nitrogen of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site PJ1982. Sample heights above ground level are denoted in brackets.

The mean foliage nitrogen concentrations for site GN1965a (Figure 6.13) consistently ranged between 0.5% and 0.8%. In 1998 the lower strata was 0.55%, decreasing to 0.47% in 1999 then increasing over subsequent years to 0.7% in 2003. Similar trends were observed for the other strata. The mean N for the middle strata was 0.5% in 1999 increasing to 0.8% in 2003. In 2000 the mean N for the upper strata was 0.5%, increasing to 0.8% in 2003.

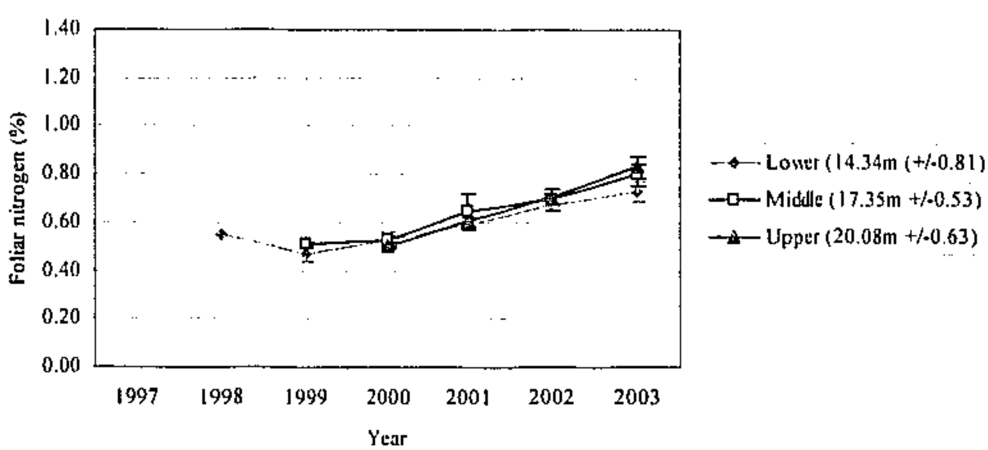

Figure 6.13: Line graph representing the mean and standard error of the percentage nitrogen of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site GN1965a. Sample heights above ground level are denoted in brackets.

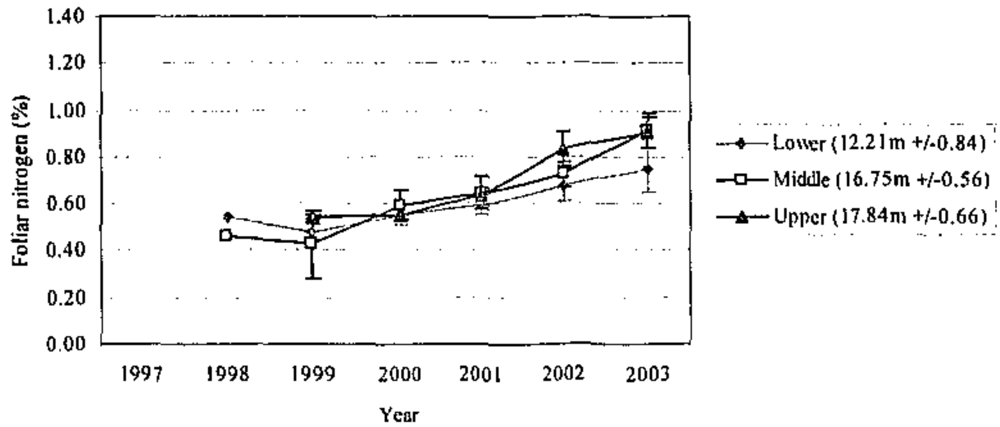

Figure 6.14: Line graph representing the mean and standard error of the percentage nitrogen of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site GN1965b. Sample heights above ground level are denoted in brackets.

Similar trends were observed at site GN1965b (Figure 6.14) as observed at site GN1965a with mean foliar nitrogen concentration commencing at 0.5%, decreasing moderately in the following year then increasing over consecutive years. The mean N of the lower strata commenced at 0.5% increasing to 0.75% in 2003. The middle stratum was 0.5% in 1998, increasing to 0.9% in 2003. The upper strata mean N was 0.5% in 1999, increasing to 0.9% in 2003

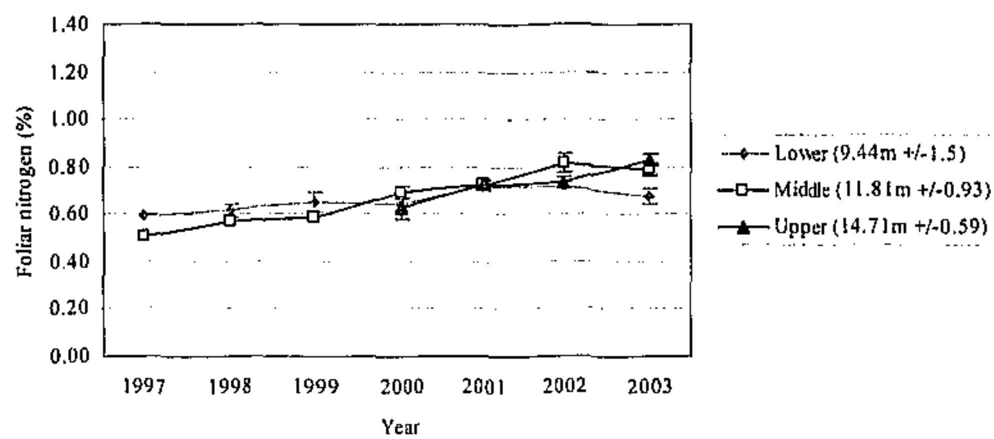

Figure 6.15: Line graph representing the mean and standard error of the percentage nitrogen of *Pinus pinaster* Ait. foliage over time. Foliage samples were obtained from the northern aspect of the lower, middle and upper stratum of the canopy at site PJ1971. Sample heights above ground level are denoted in brackets.

The mean foliar nitrogen concentration at site PJ1971 (Figure 6.15) was 0.6% in 1997, increasing to 0.7 in 2003. The decline observed in 2000 and 2001 was less than 0.05%. In 1997 the mean N for the middle strata was 0.5%, increasing over consecutive years to 0.8% in 2003. Three years of foliage was represented by the upper strata with N commencing at 0.6% in 2000, increasing to 0.8% in 2003.