Balancing Productivity and Drought Risk in Blue Gum Plantations

A Plantation Management Workshop - Jointly Presented by:

Bunnings Tree Farms
Department of Conservation and Land Management
CSIRO Forestry and Forest Products
Timbercorp Eucalypts Limited

November 9th and 10th, 1999
Karri Valley Resort, Pemberton WA, selected experiments and operational plantations

CSIRO

BUNNINGS TREEFARMS

CALM
DEPARTMENT of CONSERVATION and LAND MANAGEMENT

TIMBERCORP

Program

Day 1, Tuesday November 9, 1999

SESSION 1 – Chair, Neil Burrows (CALM)

9 a.m. Welcome. *Sadanandan Nambiar (CSIRO)*

9.10 a.m. Blue gums - history and prospects.
Richard Breidahl (Bunnings Tree Farms)

9.40 a.m. Climate and soil factors affecting productivity and drought risk.
Richard Harper (CALM), Justine Edwards (CALM/UWA) and Ted Reilly (CALM/Great Southern Plantations)

10.20 a.m. MORNING TEA

SESSION 2 – Chair, Tony Smith (Bunnings Tree Farms)

10.40 a.m. Reconciling productivity and drought risk, a regional perspective.
Stuart Crombie (CALM) and John McGrath (CALM)

11.20 a.m. Physiological and environmental influences on sustainable productivity of blue gums. *Don White (CSIRO), Chris Beadle (CSIRO) and Dale Worledge (CSIRO)*

12.00 p.m. High temperature, evaporative demand and drought: acting together to constrain plantation productivity and increase risk.
Craig Macfarlane (UWA), Mark Adams (UWA) and Don White (CSIRO)

12.30 p.m. LUNCH

SESSION 3 – Chair, Ian Bail (Timbercorp)

1.30 p.m. Nitrogen, plantation growth and water use.
Ingrid Krockenberger (Murdoch University), Don White (CSIRO), Richard Bell (Murdoch University) and Bernie Dell (Murdoch University)

1.50 p.m. Management options for plantations in WA's Mediterranean climate.
John McGrath (CALM)

2.10 p.m. Adapting site selection and growth prediction in southwestern Australia.
Tony Smith (Bunnings Tree Farms)

2.35 p.m. Developing management tools for balancing productivity and drought risk in blue gums.
Stuart Crombie (CALM), Don White (CSIRO) and Tony Smith (Bunnings Tree Farms)

3.00 p.m. AFTERNOON TEA

3.15 p.m. Panel discussion – chaired by Chris Shedley

4.15 p.m. Summing up - Sadanandan Nambiar (CSIRO)

Day 2, Wednesday November 10, 1999

9.00 a.m. – Depart Karri Valley

9.45 a.m. – Arrive Avery's Tree Farm

12.00 a.m – Depart Avery's Tree Farm

12.45 a.m. – Arrive Carpenters Tree Farm

2. 00 p.m – Depart Carpenters Tree Farm

2. 25 p.m – Return Karri Valley

2. 40 p.m. Those requiring a lift to Perth – be on the bus

Lunch at Carpenter's Tree Farm supplied by:

TIMBERCORP

Contact details of workshop contributors

Dr Sadanandan Nambiar, Program Manager – Plantations and Farm Forestry, CSIRO Forestry and Forest Products, PO Box E4008, ACT 2600

Mr Richard Breidahl, Bunnings Tree Farms, PO Box 444, Manjimup, WA 6258

Dr Richard Harper, CALM Science and Information Division, Locked Bag 104, Bentley Delivery Centre, Bentley, WA 6983

Ms Justine Edwards, Botany Department, University of Western Australia, Nedlands, WA 6907

Mr Ted Riley, Great Southern Plantations, 1 Rose St, Manjimup, WA 6258

Dr Stuart Crombie, CALM Science and Information Division, Locked Bag 104, Bentley Delivery Centre, Bentley, WA 6983

Dr John McGrath, CALM Science and Information Division, Locked Bag 104, Bentley Delivery Centre, Bentley, WA 6983

Dr Don White, CSIRO Forestry and Forest Products, Private Bag, PO Wembley, WA 6014

Dr Chris Beadle, CSIRO Forestry and Forest Products, GPO Box 252-12, Hobart, Tas 7001

Mr Dale Worledge, CSIRO Forestry and Forest Products, GPO Box 252-12, Hobart, Tas 7001

Mr Craig Macfarlane, Botany Department, University of Western Australia, Nedlands, WA 6907

Dr Mark Adams, Botany Department, University of Western Australia, Nedlands, WA 6907

Ms Ingrid Krockenberger, Division of Science, Murdoch University, South St., Murdoch, WA 6150

Dr Richard Bell, Division of Science, Murdoch University, South St., Murdoch, WA 6150

Dr Bernie Dell, School of Biological Science and Biotechnology, Murdoch University, South St., Murdoch, WA 6150

Mr Tony Smith, Bunnings Tree Farms, PO Box 444, Manjimup, WA 6258

Dr Chris Shedley, RMB 382, Bridgetown, WA 6255

Mr Ian Bail, Timbercorp Eucalypts Limited, Technology Enterprise Centre, Suite 5, 2 Park Drive, Bundoora, Victoria 3083

BLUEGUMS - HISTORY AND PROSPECTS

Richard Breidahl
Operations Manager, Bunnings Treefarms

1. HISTORY

i) The Beginning

The first commercial planting of Tasmanian blue gum (Eucalyptus globulus ssp globulus) in Western Australia occurred at Knox plantation near Manjimup in 1980. The plantation was established on a recently cleared bush site by WA Chip and Pulp Co Pty Ltd (WACAP) from which Bunnings Treefarms evolved. WACAP's plantation program commenced because of the vision of its then Managing Director, John Oldham, who felt that the SW of Western Australia had the soils, rainfall and sunshine to meet what he saw would be a rapidly increasing demand for wood products in the Asian region. This vision was reinforced by trips to Portugal in 1981 and Brazil in 1983 where John viewed vast areas of eucalypt plantations exclusively feeding major pulp mills.

Blue gum was selected for the initial and subsequent plantings after considerable study because it;

- was proven in Mediterranean climates.
- had demonstrated rapid growth in local plots.
- had very desirable pulping qualities.
- was resistant to Phytopthora (jarrah dieback).
- had the ability to reshoot (coppice) from the stump.
- had the potential for other uses eg sawn timber, veneer.

Many of these reasons still hold today although the widespread planting of the species over an enormous range of environments have proved that it does have its limitations. This was the catalyst for the project on "Balancing Productivity and Drought Risk in Blue Gum Plantations" and this resulting seminar.

ii) 1980 - 1985

Between 1980 and 1985 WACAP remained the only group establishing commercial blue gum plantations but planting levels were very low (< 200 ha/annum). The most significant development during this period was the first commercial planting on a pastured site which occurred at Channybearup Treefarm near Manjimup in 1981. It wasn't long before the enormous improvements in growth rates on pastured sites became obvious, which eventually led to the phasing out of plantings on bush sites later in the 1980's.

iii) 1986 - 1990

The industry received a tremendous boost between 1986 and 1990 with the launching of CALM's Tree Trust Program. This vision initially led to the establishment of about 5,000 hectares in 1988/89 funded by the State Government. These plantings were especially important as they introduced the concept of leasing land from farmers which was to become so important during the 1990's. The industry received another boost in 1988 with WACAP receiving a National Afforestation Program (NAP) grant to expand its commercial plantation activity. This led to a more than doubling of WACAP's program to over 1,000 ha/annum by the end of the period.

iv) 1991 - 1995

The period from 1991 - 1995 saw a continuation of the rapid expansion of the industry. This occurred due to a further increase in WACAP's (now Bunnings Treefarms) activity, the consolidation and subsequent expansion of CALM's program, now funded by international pulp and paper companies and the emergence of a number of significant new players. These new players were mostly prospectus groups and included Timbercorp, Australian Eucalypts, Integrated Tree Cropping, Pacific Forestry and WA Bluegum. Annual plantings increased from about 2,000 ha/annum at the start of the period to over 10,000 ha/annum at the end. Commercial harvesting operations commenced during this period and resulted in the initial exporting of about 30,000 tonnes of woodchips to Japan in 1994. Another significant development that occurred during this period was a major drought during the summer and autumn of 1993/94 which resulted in widespread deaths in some 3 - 6 year old plantations. The deaths which occurred on sites that were shallow to bedrock or had impenetrable hardpans near the surface, caused a major rethink within the industry with regard to site selection. In Bunnings Treefarms it led to the routine drilling of all sites to a depth of 2.1 metres.

v) 1996 - 1999

In the last half of the 1990's plantings have continued to increase dramatically with more than 20,000 hectares being established in each of the last three years. The plantings are now dominated by the Prospectus groups and to a lesser extent CALM's international clients. While the plantings in the first half of the decade were mostly on leased land, purchases have become more important again over the last few years as the requirement for land has increased. Harvesting continued throughout this period with annual woodchip exports to Japan doubling from 50,000 tonnes in 1996 to 100,000 tonnes in 1999.

THE PRESENT

As a result of all this activity there are now about 120,000 hectares of blue gum plantations in Western Australia. These plantings will result in an increase in wood production from the current level of about 100,000 tonnes/annum to more than 5 million tonnes/annum by 2007. Currently virtually all the woodchips are being produced at Bunnings Diamond Mill just south of Manjimup. The woodchips are then railed to the port of Bunbury for export to Japan. This is inefficient especially for plantations situated north of Manjimup and as a result Bunnings have recently installed a mobile chipper on a plantation near Bunbury to handle this material. Upgrading has commenced at the Bunbury port to handle the rapidly increasing volume of plantation material and feasibility studies for new chipmills at Bunbury and Albany are almost complete. These new plants are expected to be operational in 2001.

THE FUTURE

Future challenges for the industry include:

i. Marketing the rapidly increasing volumes over the next 5 - 10 years which includes finding new markets for woodchips as well as new products.
ii. Ensuring that past mistakes in land selection are not repeated.
iii. Ensuring that the full potential of the sites are realised through the use of the best available genetic material, and silvicultural practices (including insect control).
iv. Significantly reducing harvesting costs in line with world's best practice.
v. Ensuring that the new players in the industry fund research programs as has been done in the past by government agencies and the large vertically integrated forestry companies.

Performance of *Eucalyptus globulus* plantations in south-western Australia in relation to soils and climate

R.J. Harper[1], J.G. Edwards, J.F. McGrath, T.J. Reilly & S.L. Ward

CALMScience, Department of Conservation and Land Management, Locked Bag 104, Bentley Delivery Centre, WA 6983.

SUMMARY

Several interacting factors were found to affect the early performance of blue-gum (*Eucalyptus globulus*) plantations planted on farmland in south-western Australia. These included climate (rainfall, evaporation), soil volume (estimated by soil depth, occurrence of ferricrete gravel), soil fertility (total N content) and stocking. These factors all point to water supply as being the critical factor in plantation performance in this region, with growth increasing with increasing rainfall and decreasing evaporation. Similarly, they suggest that both the location of trees in the landscape (slope position) and planting conformation (strips integrated with farming) will become more important with decreasing rainfall and increasing evaporation. Response to nitrogen fertilization is expected on sites with poor existing nitrogen fertility and an adequate moisture supply.

Many soil attributes that are important for blue-gum performance (soil depth, soil fertility, soil salinity) are not measured in regional soil surveys; those soil attributes which are measured (soil profile form, texture, colour) are not, or only poorly related to blue-gum growth. Thus, regional mapping (1:50 000 – 1:100 000 scale) may be of marginal value in predicting blue-gum productivity. Site surveys of key soil attributes *are required* at scales of 1:10,000 to 1:20,000 prior to planting, with an appropriate observation density. Information from these surveys may also be interpreted for site-specific management.

Potential changes to site selection practice include taking into account rainfall (current limit 600 mm), annual evaporation and soil fertility; however any changes will depend on an economic analysis including transport distances and land costs. Existing recommendations of not planting shallow (<2m to a root impeding layer), saline soils and deep sands (sand horizons >2 m deep) remain.

INTRODUCTION

The establishment of blue-gums (*Eucalyptus globulus)* on farmland represents a major new industry in south-western Australia, with 130,000 ha established in the last 10 years and a mean rate of establishment of 26 000 ha/year over the last three years (Love *et al.* 1999).

The aims of this study were to:

- determine the relationships between blue-gum performance (as measured by survival and growth) and various site (soil, geomorphological and climatic) attributes,
- determine if regional (1:50 000 – 1:100 000) scale soil-landscape mapping was useful for plantation selection, and
- revise current site selection guidelines for planting *E. globulus* on farmland.

It should be noted at the outset that much of the data presented here are from 6 year old trees. Mean growth at age 6 is not linearly related to that at final harvest (10 years.) Similarly, silviculture and genetic material has improved substantially since many of these plots were established. Poor establishment, and changes in site selection practice, are partly accounted for by deleting those plots from this analysis.

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[1] richardh@calm.wa.gov.au

Presentation to "Balancing Productivity and Drought Risk in Blue Gum Plantations" Karri Valley Resort, Pemberton, Western Australia, 9-10 November, 1999.

MATERIALS & METHODS

467 permanent sampling plots were established in 113 *E. globulus* plantations located in farmland between Perth, Augusta and Esperance in south-western Australia. The plantations were established between 1988 and 1992, with a mean stocking of 929 trees/ha. Plots were between 250 and 400 m^2 and covered the range of health, productivity, landscape position and soils found within the plantings. Plot performance was estimated from top height (tallest 75 trees/ha), volume (using the cone formula with top height and basal area) and mortality (proportion of dead trees).

Soils were examined at each plot, to depths of up to 4.5 m, via either backhoe pits or auger holes. Soil profile and landscape attributes were described using the procedures of McDonald *et al.* (1990). Surface samples (0-10 cm) were analysed for an array of physical and chemical properties, with clay content and total nitrogen reported here.

Climatic variables were derived for each plot location using ESOCLIM (McMahon *et al.* 1995), with mean annual rainfall ranging between 507 and 1443 mm.

RESULTS & DISCUSSION

1. The major factor affecting blue-gum performance in south-western Australia is climate

Two major components of climate affect blue-gum performance (Fig. 1). The first is associated with mean annual rainfall, the second with a north-south gradient of several environmental attributes including maximum temperature, radiation and evaporation. Northern sites have harsher growing conditions, particularly during summer, than those in the south. Fig. 1 has been developed for 240 plots with reasonable stocking (>800 stems/ha) and site properties currently considered to be suitable. Blue-gum growth is strongly affected by climatic conditions, with a marked increase in growth with increasing rainfall and decreasing evaporation.

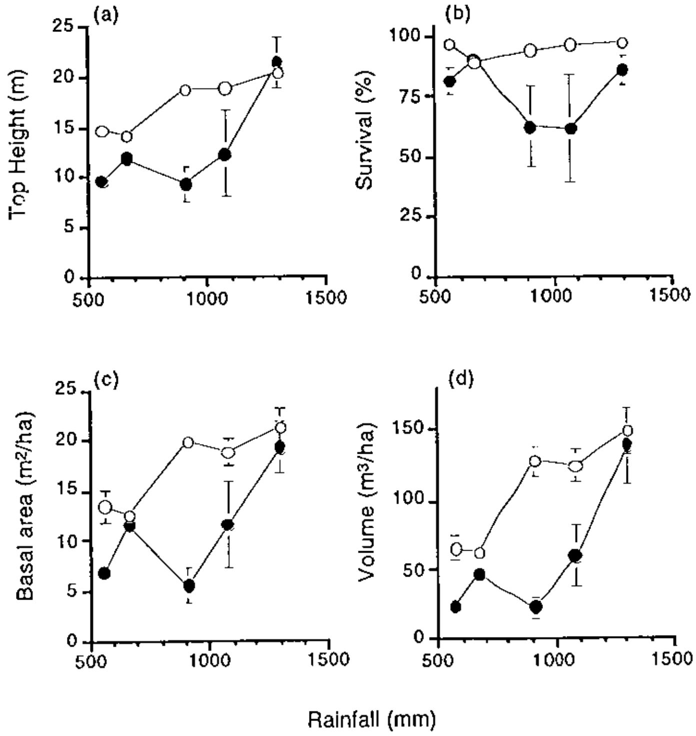

Fig. 1 Performance of 6-year-old *Eucalyptus globulus* planted on farmland across south-western Australia, in relation to major climatic attributes. Plots with >2 m soil, EC <50mS/m and >800 stems/ha at establishment. O <1500 mm, ● >1500 mm total annual evaporation.

Table 1 Estimated volume of trees at 10 years old from measurements taken at age 6, using the Inions (1992) growth models. Plots with >1000 stems/ha at 6 years old and non-saline soils, >2 m deep.

Evaporation (mm)	Rainfall (mm)					
	600-800			>800		
	n	Volume[A]	Volume[B]	n	Volume[A]	Volume[B]
		(m³/ha)			(m³/ha)	
<1500 (South)	18	158±12	163±13	47	238±12	257±17
>1500 (North)	37	102±4	129±10	C		

[a]A: Predicted volume – TH and stocking model of Inions (1992) from age 6 data
[c]B: Corrected volume – corrected using basal area from age 6 data
C: no plots with >1000 stems/ha

There are no fully stocked plots available to measure final harvest (10 year) yields. Using growth formulae developed by Inions (1992), 10 year old volumes were estimated from 6 year growth data (top height, stocking and basal areas), for plots with >1,000 trees/ha and on deep, non-saline soils (Table 1). This gives an indication of the potential growth in these areas, without taking into account the risk of drought in the latter stages of the rotation.

2. Adequate soil volume is essential for plantation survival

The current soil depth guideline of >2 m to root impenetrable material (Harper *et al.* 1998) was determined from a study of 3 plantations in the Darling Range. Survival at 6 years of age was not related to rainfall, but to annual evaporation and soil volume (Table 2), with the current guideline of >2 m of soil holding well in the southern zone, but being less successful in the northern zone.

Table 2 Survival (as % of trees surviving establishment) and growth of 6 year old plantations of *Eucalyptus globulus* in relation to soil depth and annual evaporation. Plots with >800 trees/ha at age 3.

Evaporation (mm)	Soil depth (m)			
	<2		>2	
	No. plots	Surv.	No. plots	Surv.
		(%)		(%)
<1500 (South)	20	50	146	93
>1500 (North)	18	56	95	84

As the current older plantations are under-stocked it is not possible to determine whether this soil depth (2 m) is adequate to maintain survival and productivity to age 10. Similarly, climatic data are means and do not take into account the probability of successive droughts. Drought is a recurrent feature of the south-western Australian environment (McGrath *et al.* 1991; Hingston *et al.* 1998).

A useful surrogate for soil depth is the occurrence of ferricrete gravel, which often indicates the occurrence of deep weathering (laterite) profiles. These weathering profiles may be many metres deep. The distribution of soil depth has a geomorphic basis, being related to patterns of regolith stripping, thus it may be possible to develop regional indicators of drought risk (Harper and Smettem, in prep).

3. Plantation productivity is related to stocking

The success of tree establishment increased systematically with planting year with a mean of 754 trees/ha for the P88 plantations and 875, 968, 1088 and 1120 trees/ha for the P89. P90, P91 and P92 plantations respectively. Thus, there are currently very few plots near harvest age with full stocking.

There were large responses in tree volume at age 6 to increases in plantation density across the southern zone (irrespective of rainfall) and in the high rainfall areas of the northern zone (Fig. 2). There were no effects on top height or survival.

It may be possible to further increase production with higher rates of stocking, however this has to be balanced with harvesting issues such as log size. Similarly, larger canopies may predispose fully stocked plantations to greater risk of water stress and of drought in dry years, although there are no data to test this assumption.

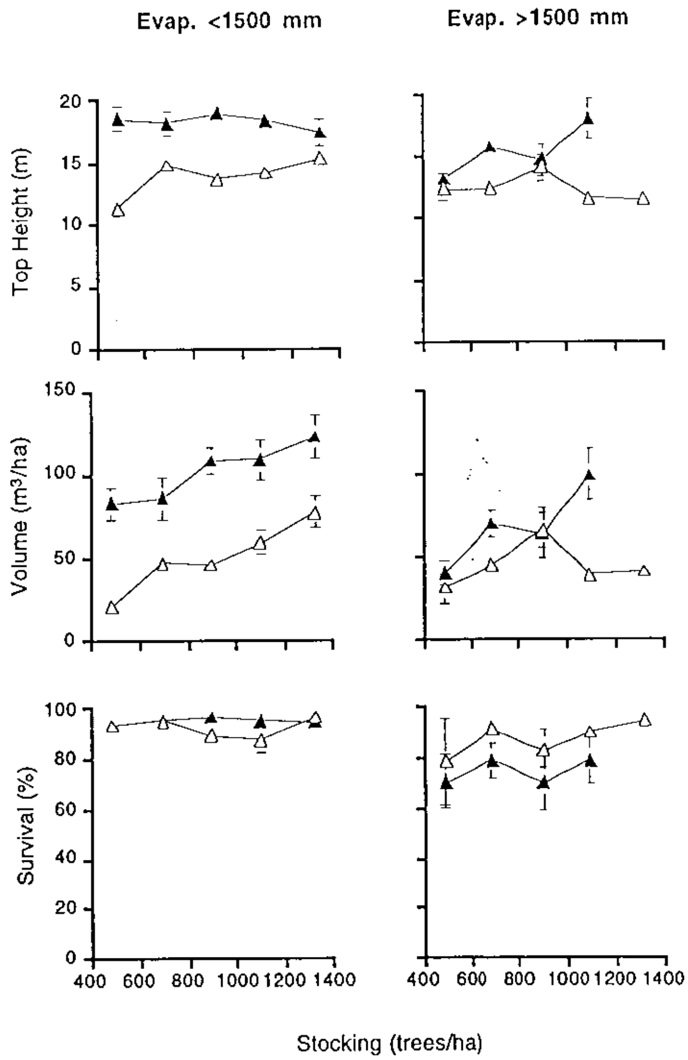

Fig. 2 The effects of initial stocking and climate on blue-gum growth at 6 years. Plots with >2 m soil, EC <50 mS/m. 600-800 mm (Δ) and >800 mm (▲) rainfall zones.

4. Strong growth responses to soil fertility in non-water limited areas

There were strong effects of soil fertility on volume, as measured by soil total nitrogen (N) content (%), particularly in the higher (>800 mm) rainfall zone. Increasing total N content from 0.1 to 0.4% increased volume production from 60 to 150 m³/ha in the low evaporation zone and from 40 to 120 m³/ha in the high evaporation zone. These responses did not occur in the 600-800 mm rainfall zone.

Total N content may be associated with a range of other soil attributes, such as texture, which influence nutrient and water supply and hence growth. It is highly likely that there will be a strong response in existing plantings to N fertilization, where soil total N contents are low and there is an adequate moisture supply.

There were no apparent responses to available soil phosphorus content, which is consistent with CALM's trial studies.

5. Several soil properties are critical indicators of blue-gum performance

Apart from the depth to basement rock or saprolite, other field soil attributes which were consistent indicators of tree performance included the occurrence of deep (>2 m) sands and the presence of ferricrete gravel. The soil depth considered critical for blue-gum survival (2 m) is much deeper than that traditionally measured in soil surveys. Deep sands are likely to affect growth through poor nitrogen fertility, as a consequence of poor previous pasture growth, and poor water holding capacity (Edwards and Harper 1996a; Edwards and Harper 1996b). As described earlier, the occurrence of ferricrete is related to the occurrence of deep weathering profiles.

Several soil attributes that are traditionally measured in soil surveys, such as colour, structure and field texture did not significantly affect blue-gum performance across the region, although some of these may be important at more localized scales.

These findings have implications for the use of regional soil surveys to predict blue-gum performance. Many soil attributes that are important for blue-gum performance (soil depth, soil fertility, soil salinity) are not measured in regional scale (1:50 000 – 1:100 000) soil surveys; those soil attributes that are measured (soil profile form, texture, colour) are not, or only poorly related to blue-gum growth. Thus, apart from considerations of inappropriate mapping scale for management purposes, the regional mapping may be of little use in predicting blue-gum productivity.

Site surveys of key soil attributes *are required* at scales of 1:10,000 to 1:20,000 prior to planting, with an appropriate observation density. Information from these surveys may also be useful for site-specific management (Harper and McGrath 1997). Remotely sensed techniques, such as gamma radiometrics, which discriminate between soil properties (Wong and Harper 1999) may be useful to delineate broad soil groups, and reduce the cost of site surveys.

Conclusions

The several interacting factors which were found to affect blue-gum performance (climate, soil volume, soil fertility and stocking) all point to the importance of water supply as being the critical factor in plantation performance in this region. This suggests that both the location of trees in the landscape (slope position) and planting conformation (strips integrated with farming) will become more important with decreasing rainfall and increasing evaporation. Responses to nitrogen fertilization are expected on sites with poor existing nitrogen fertility and an adequate moisture supply.

ACKNOWLEDGEMENTS

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Reconciling productivity and drought risk: a regional perspective

Stuart Crombie and John McGrath
CALMScience

Introduction

Plantation growing of *Eucalyptus globulus* is a new industry in the south west of WA (e.g. Shea 1998). Quantitative data regarding many of the relationships between biophysical factors and tree growth are now becoming available.

Water availability is emerging as one of the primary determinants of tree growth as rainfall and evaporative demand appear to be major components of site potential (Harper *et al.*, this workshop). However, rainfall effectiveness can vary depending on the water storage capacity of soils, determined primarily by soil type and depth but also by topography, which affects water flows, and by soil macropores which can affect infiltration and runoff. Water may be unavailable to trees if root access is prevented by impeding layers or in soils impenetrable to roots, in salty or in saturated zones (Smettam et al. 1999).

The water deficits and growth of *Eucalyptus globulus* in plantations across rainfall gradients and on different soil types are reported. Also, the effect of specific local soil factors, including soil depth, on tree water status are discussed with reference to examples found in this study.

Water deficits in *Eucalyptus globulus* in south-west Western Australia

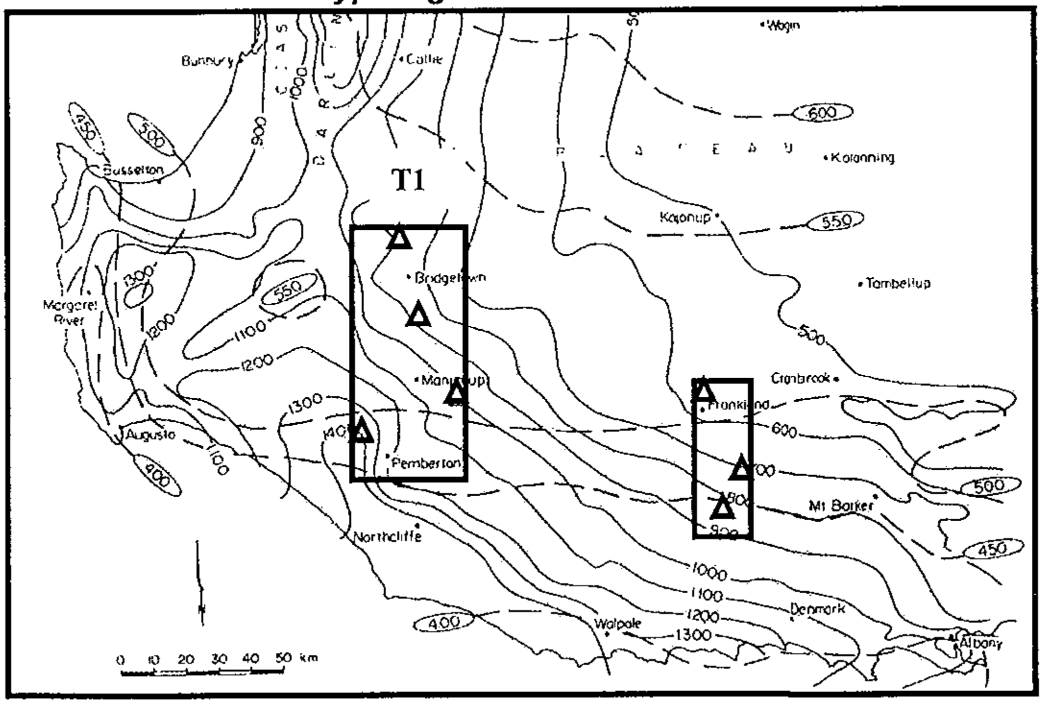

Figure 1. Location of transects. Map of south-west WA from Gentilli (1989).

Sites were selected along two transects down the rainfall gradient in the south west of WA in 1995 and 1996. Sites and plots of both transects were co-located with site assessment and growth plots used by Harper and Edwards and described at this meeting.

Transect 1

The first transect was in 6-7 year old plantations from Pemberton north to Greenbushes (Transect 1, Figure 1). Water potentials of drill spoil from the surface to approximately 9 m was determined using the filter paper technique in late spring (October/November 1995). Soil under pasture at Greenbushes was found to be near field capacity to about a metre from the surface. The water potential of the driest part of the profile is an indicator of the extent to which trees have dried the profile.

Soil water potentials ranged from near field capacity (under pasture) and -0.7 MPa at Pemberton to -3.4 MPa under trees at Greenbushes. The trend in soil water potential roughly paralleled the gradients of decreasing rainfall and increasing evaporation from Pemberton to Greenbushes (Figure 2). Hingston et al. (1998) reported similar summer water deficits in *Eucalyptus globulus* measured using the pressure chamber at nearby Mumballup (-3.4 MPa). Standing volume along the Pemberton to Greenbushes transect fell from 271 m^3 ha^{-1} near Pemberton to 209 m^3 ha^{-1} near Greenbushes.

It was apparent from this limited work that as rainfall increased soil water depletion decreased, implying that rainfall satisfied a greater proportion of evaporative requirements. Work on this transect was discontinued when two of the plots were harvested.

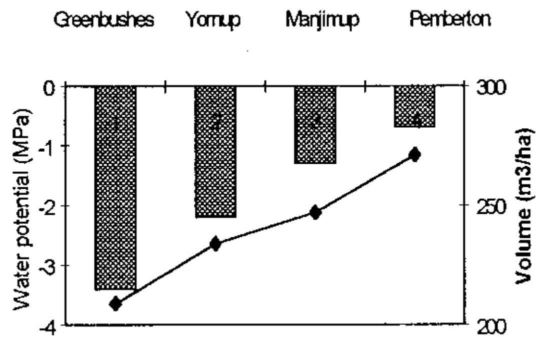

Figure 2. Water potentials of the driest part of the soil profile and standing volumes of plantations on T1 from Pemberton (rainfall 1191 mm $year^{-1}$), through Manjimup (1020 mm), Yornup (850 mm) to Greenbushes (860 mm).

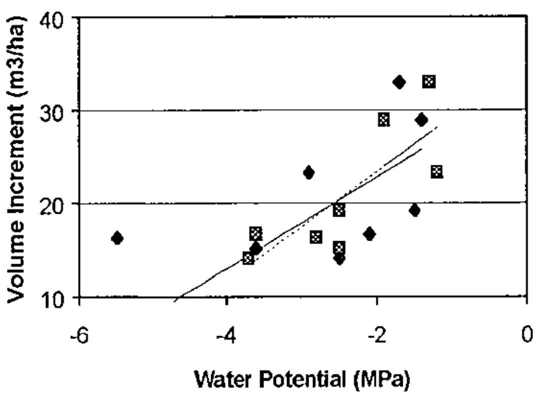

Figure 3. The effect of water deficit on annual volume increment along transect T2 from 900 mm to 560 mm annual rainfall. Squares and dotted line= soil water potential by filter paper.

CAI = 32.6 + 4.9(Soil WP), r^2=.31

Circles and solid line = dawn leaf water potential by Scholander Bomb.

CAI =35.2 + 5.9(Leaf WP), $r^{2=}$.64 (both regressions exclude outlier).

Transect 2.
Another, larger, transect survey including direct measurement of tree water status was run from August 1996 to February 1998 (Smettam et al. 1999). In this transect three sites ranging from a low rainfall, high evaporation site (8 km north of Frankland, 560 mm rainfall), through a moderate rainfall sites (Perilup on Muir Highway, 780 mm rainfall) to a high rainfall site (Table Hill, 900 mm rainfall) were selected.

Dawn leaf water potentials in mid-February 1998 were below –2.5 MPa on all three Frankland sites and on two of the three plots at Perilup. Also, strong relationships were found between growth (expressed as CAI) and water availability (measured as water potential either of leaves at dawn in the driest month or of the driest part of the soil profile) were found (Figure 3).

Tree water potentials at the two driest plots at Perilup and all three plots at Frankland declined by an average of 1.6 MPa) between mid-December 1997 and mid-February 1998. This suggests that very little water was available to trees at above wilting point in mid to late summer.

Rainfall variability
Rainfall in the south-west of WA is quite variable. Consequently, long-term rainfall averages may be a relatively insensitive indicator of water availability to trees when 10 and 20 year rainfall minimums may be 70% or less of long-term averages as at Pemberton and Mt Barker (Figure 4a, b).

Plantations on sites with substantial amounts of water available at the end of summer in normal years will be likely to experience less severe water deficits in dry years than those without such water reserves. In the examples above, plantations at Pemberton and Manjimup (Figure 2) and Mulcahy Road (Figure 3) were found to have water available at above wilting point deep in the profiles. These sites are likely to be able to maintain higher water potentials during dry years than those at Yornup or Greenbushes (Figure 2) or Perilup and Frankland (Figure 3).

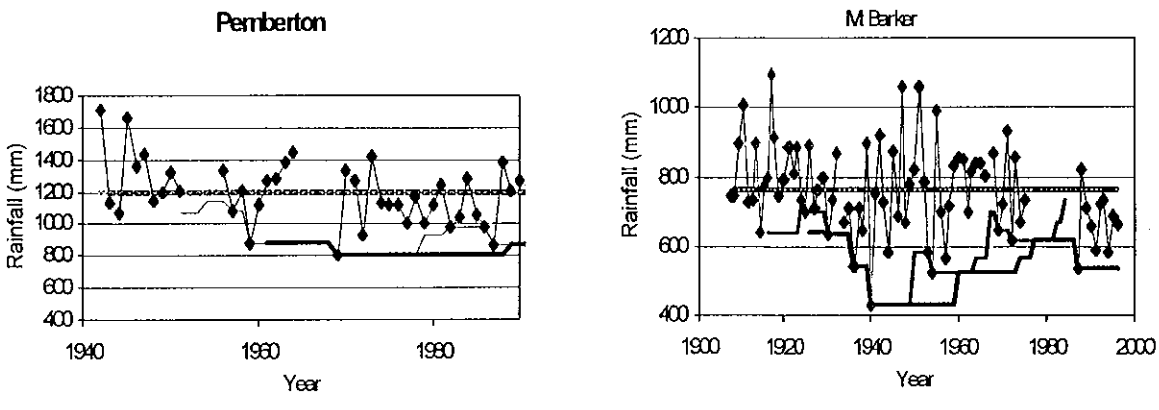

Figure 4 a,b.Annual rainfall at a) Pemberton and b) Mt Barker showing long-term average (dotted line), running 10 year minimum (thin line) and running 20 year minimum (thick line)

The interaction of stored soil water drawdown and tree water deficits in near average years and years with substantially less rainfall needs investigation.

Silvicultural options may be available to increase the "buffering" of sites against one or two year periods of below average rainfall.

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Physiological and environmental influences on sustainable plantation productivity

Don A White[1], Christopher L Beadle[2] and Dale Worledge[2]

1 CSIRO Forestry and Forest Products, Wembley, WA
2 CSIRO,Forestry and Forest Products, Hobart, Tasmania

Background

In south western Australia, blue gum (*Eucalyptus globulus*) plantations were established at a rate of about 20 000 ha per year during 1996, 1997, and 1998. The current plantation estate covers approximately 100 000 ha and will expand further in coming years. Plantations are established on agricultural land primarily for wood fibre. Therefore management is aimed at maximising growth. For achieving sustained productivity good genetic stock and sound management of soil based resources are required. There is already substantial research underway aimed at improving soil management practices.

Studies in south western Australia indicate that soil and climatic factors influencing the supply of water have the major influence on the growth and survival of blue gums (Inions 1991, Edwards and Harper 1996a and b). During the summer of 1993/94, when only 45 mm of rain fell between October and May, a significant area of blue gums plantations died from water stress (Dutkowski 1995). Rooting depth (soil water storage capacity) has been identified as a major soil factor influencing the survival of blue gums under drought conditions (Harper 1994a). Moreover, on sites with either limited soil water storage or marginal rainfall, increasing growth by fertilization and hence increasing the demand for water, has led to increased tree mortality (McGrath unpublished). While significant progress has been made in identifying problem sites (Harper 1994b), drought deaths continue to occur in blue gum plantations in south western Australia (Figure 1).

Observed mean annual increments in the extant blue gum estate vary from 5 to 35 m^3 ha^{-1} (e.g. Hingston 1994). These compare with an industry expectation of 20-25 m^3 across the estate. Synchronising actual and expected growth rate under conditions of variable available water and quantifying the risk of drought deaths are essential prerequisites to the development of appropriate management strategies for blue gum plantations. This will require development of robust relationships amongst available water, productivity, water use and the development of water stress in blue gum plantations.

Blue gums in Mediterranean south western Australia

The drought physiology of blue gums is consistent with a species that is well adapted to short periods of water stress punctuated by rainfall, but is vulnerable to prolonged rain free periods (White et al. 1996; White 1996; Honeysett et al. 1996; White et al. 1998; White et al 1999; White et al. 2000). The Mediterranean climate of south western Australia is characterised by markedly seasonal rainfall with hot dry summers and cool wet winters. This poses particular challenges for managing water relations of blue gums, which occur naturally in temperate climates having more uniform rainfall distribution patterns (Figure 1). In our environment the relationship between the distribution of rainfall and soil water storage capacity is critical. On sites which do not store enough water to buffer the substantial deficit between summer rainfall and evaporative demand (Figure 2), the physiological strategies which enable the rapid growth of blue gums render them vulnerable to drought death during prolonged rain-free periods. There is little understanding of the physiological responses, and therefore growth and survival of blue gums, in this markedly seasonal climate. Such an understanding would help us to develop management options and eventually incorporate physiological information in breeding programs.

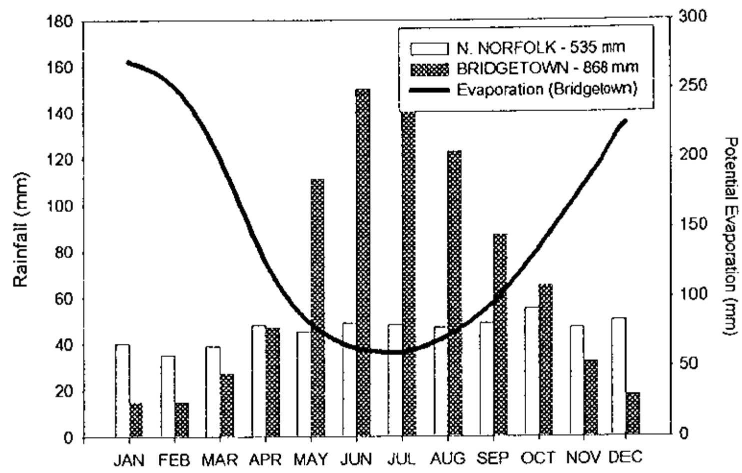

Figure 1. Mean monthly rainfall for New Norfolk (Tasmania) and Bridgetown (WA). Also shows monthly pan evaporation for Bridgetown. New Norfolk is within the natural range of blue gums while Bridgetown falls within one of the major plantation centres in south western WA.

A Conceptual Framework for New Research

Leaf area index (a measure of canopy size) is a key determinant of the amount of radiation intercepted and absorbed by forest canopies and is therefore a critical determinant of both growth (Linder 1985, Battaglia and Sands 1997) and water use (White 1996; White et al. 2000). Understanding the dynamic relationship between environment and leaf area index is therefore central to the prediction of plantation growth. Moreover, it has been reported that there is a relationship between leaf area index measured at age two years and stem growth at age 8 years in blue gum plantations in south eastern Australia (Nambiar 1995). Despite this there is little knowledge of the dynamics of leaf area development in blue gums, particularly in a Mediterranean environment.

In south western Australia site selection and prediction of site productivity are critical. In principle, practices that maximise leaf area index and promote canopy health will maximise productivity. However on sites where water storage is limited, practices which maximise growth will also increase the risk of tree deaths.

Leaf area index will be determined by stocking, soil fertility and available water, all of which may be managed. For any given set of site conditions there may be a particular leaf area index that will maximise plantation growth. Thus the dynamic relationship between leaf area index and available water is a critical factor for management. This is particularly important in south western Australia where there is extreme seasonality of water availability and large canopies may develop during winter and spring and thereby increase the likelihood of tree deaths during summer drought. The management problem is to achieve high growth rates while minimising the risk of tree deaths due to summer drought.

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High temperature, evaporative demand and drought: acting together to constrain plantation productivity and increase risk.

Craig Macfarlane, Mark A. Adams, Donald A. White

The high intensity of solar radiation and relatively warm winter temperatures in south-western Australia would appear to create the potential for rapid growth of plantations. For example, assuming that:

- total annual solar radiation in Pemberton, Φ_s, is 6.8 GJ m^{-2}
- canopy cover is 100 %
- the albedo of vegetation, α, is 19 %
- maximum radiation use efficiency, a_c, is 1.8 g C MJ^{-1}
- maximum carbon conversion efficiency, ε, is 0.7 g $C_{biomass}$ g^{-1} $C_{assimilated}$
- 60 % of carbon in biomass is partitioned to stem wood, $\varpi_s = 0.6$.
- 1 g of carbon produces 2.42 g wood of mean wood density, ρ_s, 550 kg m^{-3}

then the theoretical annual increment (AI) of wood in Pemberton, W.A., would be about 91 m^3 ha^{-1} from Eq. 1 (after Landsberg and Waring, 1997).

$$AI = \frac{2.42(1-\alpha)\Phi_s a_c \varepsilon \varpi_s}{\rho_s} \qquad \text{Eq. 1}$$

However, the largest observed AI in W.A. is only two-thirds of and the largest mean AI is only about half of this. It is evident that all the radiation is not intercepted and that the radiation use efficiency and carbon conversion efficiency are less than maximum.

Carbon in biomass derives from carbon dioxide gas that diffuses through the stomata of plants into the internal air spaces of their leaves across a concentration gradient. Inside the leaf, CO_2 is fixed by the metabolic process of photosynthesis which requires solar energy. The estimated maximum rate of carbon fixation per unit of solar radiation is 1.8 g C MJ^{-1} (Landsberg and Waring, 1997). The sugars produced are transported through the plant and used to build plant tissues such as wood, roots, branches, leaves and other biomass components. Unlike photosynthesis which utilises solar energy, the energy for growth derives from oxidation of some of the assimilated carbon by the metabolic process of respiration. Hence, not all assimilated carbon becomes new biomass. 70 % is about the maximum observed proportion of assimilated carbon incorporated into new biomass (carbon conversion efficiency; Landsberg and Gower, 1997).

The efficiency of radiation use and carbon conversion both decrease as conditions become less favourable for growth and both carbon assimilation and growth may cease entirely during extremely stressful conditions. Growth is directly or indirectly affected by all environmental factors. For example, temperature directly affects the metabolic processes of photosynthesis (Battaglia et al., 1996) and respiration (Criddle et al., 1999) and thus directly affects the efficiency of both radiation use and carbon conversion. Drought (resulting from low rainfall or shallow soil) and large rates of potential evaporation indirectly cause reduced radiation use efficiency by causing stomata to close, thus restricting the diffusion of CO_2 into leaves and reducing photosynthetic rate and carbon assimilation.

In March 1998, I assessed the effects of drought and evaporative demand on carbon assimilation using measurements of stomatal conductance and net photosynthesis of two stands of *E. globulus* between Bridgetown and Boyup Bk. (Macfarlane, 1998). Relationships between stomatal conductance, and soil water deficit and evaporative demand, and between carbon assimilation and stomatal conductance, were similar to those of *E. globulus* stands in Tasmania and Portugal. Water shortage reduced stomatal conductance. Stomata closed rapidly as air temperature and evaporative demand increased and net photosynthesis decreased. As a result of reduced transpirational cooling, leaf temperatures were several degrees above air temperature for much of the day.

The effect of environment on carbon assimilation is complex. For example, a large evaporative demand may reduce carbon assimilation by droughted trees but carbon assimilation by trees with access to adequate soil water may be mostly limited by high temperature despite stomatal closure in response to large evaporative demand (Fig. 1). Evaporative demand is directly related to water use (Fig. 2) and thus the depletion of soil water and increasing risk of drought. Evaporative demand is determined by the difference between the amount, or pressure, of moisture the air can hold and the amount of moisture in the air (generally termed vapour pressure deficit or VPD). Warm air can hold more moisture than cool air so, for a given water vapour pressure (a measure of absolute water content), warm air has a greater deficit of water. The water vapour pressure of air at St. Helens, Tasmania is similar to that in drier parts of south-western Australia but less than that in wetter and more southerly parts of W.A. Higher temperatures in W.A. are mainly responsible for larger vapour pressure deficits and potential evaporation rates in W.A. than in St. Helens. Thus, in addition to direct effects on metabolism, higher temperature indirectly increases drought risk.

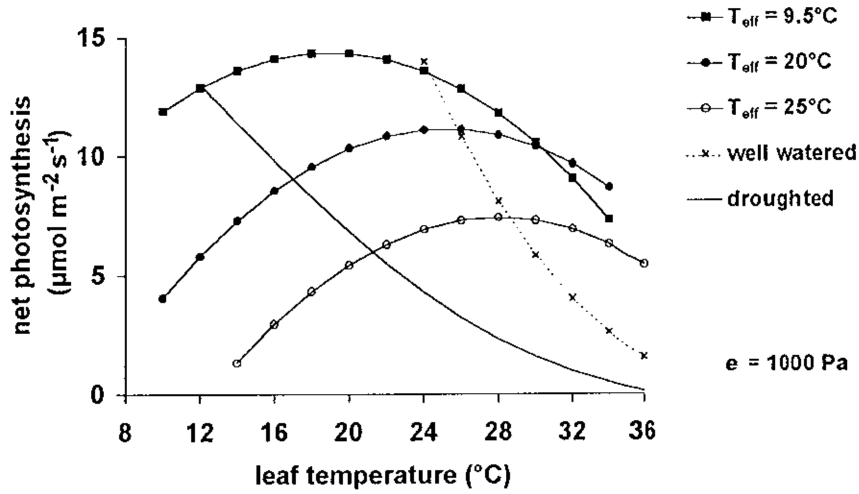

Fig. 1. The rate of net photosynthesis of sunlit leaves is determined by leaf temperature, acclimation to the effective growing temperature (T_{eff}) (Battaglia et al., 1996) and stomatal closure in response to drought and evaporative demand (Pereira et al., 1987; Macfarlane, 1998). In this figure the lines with symbols are the predicted rates of temperature dependent net photosynthesis while the other two lines are the stomatal conductance dependent rates of net photosynthesis assuming G_{max} of 387 mmol m^{-2} s^{-1} for the well-watered tree and 200 mmol m^{-2} s^{-1} for the droughted tree. The rate of net photosynthesis is more likely to be temperature limited if trees are not droughted, especially if growing temperatures are warm. As drought severity increases, photosynthesis becomes conductance limited at lower temperatures. Under conditions of warm temperature and drought, such as found in marginal areas of W.A., photosynthesis is small at all temperatures. It was assumed that conductance, G, decreases with increasing evaporative demand, D, according to the equation $G = G_{max}$ EXP(-0.63D). D is calculated from leaf temperature assuming ambient vapour pressure, *e*, of 1000 Pa.

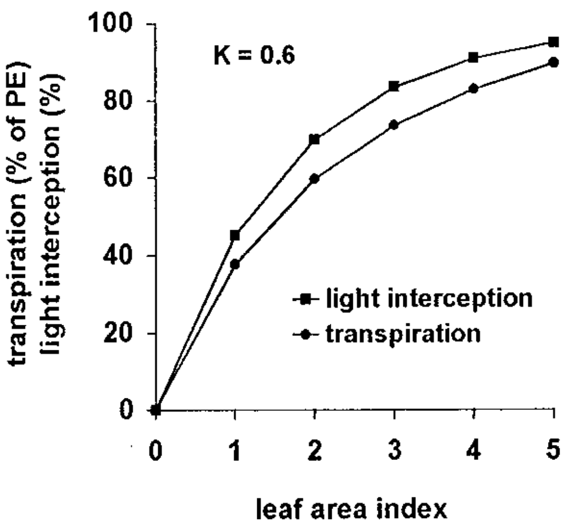

Fig. 2. Modelled relationship between leaf area, and light interception and transpiration under non-water limited conditions as a % of potential evaporation (PE).

Prolonged slow growth restricts future productivity because reduced leaf growth eventually results in a smaller canopy with less potential for radiation interception and CO_2 assimilation. The proportion of solar radiation intercepted decreases as leaf area decreases especially below LAI of 3 – 4 (Figure 2). Low leaf area also reduces maximum transpiration. If potential evaporation (PE) were 1300 mm $year^{-1}$ and annual rainfall 650 mm $year^{-1}$ then a leaf area of 1.5 would be the maximum that would not steadily deplete the soil water store and cause seasonal drought (assuming no runoff, drainage, soil evaporation or interception). In the longer term, only a smaller LAI is sustainable in regions where annual potential evaporation greatly exceeds annual rainfall and on shallow soils. At LAI = 1, maximum productivity predicted from intercepted radiation is less than half that of stands with complete canopy cover.

I modified the radiation use and carbon conversion efficiency in Eq. 1 using published relationships between carbon assimilation (Battaglia et al., 1996), growth (Criddle et al., 1999) and temperature, and between assimilation and stomatal conductance (Pereira et al., 1987; Macfarlane, 1998) in an attempt to answer the questions:

1. How are the radiation use efficiency, carbon conversion efficiency and wood yield of plantations in W.A., and in Tasmania, affected by temperature, drought and leaf area index?
2. What effect would selecting for increased 'drought-tolerance' (lowering maximum stomatal conductance or increasing stomatal sensitivity to evaporative demand) have on growth?

The results presented in Tables 1 and 2 are mainly intended to indicate relative differences between stands. Estimated long-term mean annual increments are overestimates for droughted stands because a constant proportion (60 %) of carbon in biomass partitioned to stem wood is assumed. An increasing proportion of carbon is allocated to roots at sites subjected to drought or with poor nutrition. $\varpi_s = 0.4$ would be more realistic for droughted sites and even smaller values for unfertilised sites.

Table 1. In the absence of drought, long-term average radiation use efficiency, a_c, and carbon conversion efficiency, ε, were greatest in the climate of Tasmania and Pemberton, W.A., and least in hot, dry parts of W.A. Long-term mean annual increments (MAI) after age five were larger for Pemberton because of the larger amount of intercepted radiation, Φ_n. Numbers in brackets are % of maximum. The effect of evaporative demand on carbon assimilation was small compared to that of temperature assuming except at Boyup Bk.

	St. Helens	Pemberton	Boyup Bk.
LAI	6	6	6
Φ_n (MJ m^{-2} yr^{-1})	4910	5290	5824
MAI$_{max}$ (m^3 ha yr^{-1})	82	88	97
a_c (g C MJ^{-1})	1.36 (76)	1.31 (73)	1.13 (63)
ε	0.47 (67)	0.51 (73)	0.42 (60)
MAI (m^3 ha yr^{-1})	42 (51)	45 (51)	37 (38)

Table 2. Seasonal drought at Boyup Bk. reduces the long-term MAI after age 5 compared to an irrigated stand. Radiation interception, Φ_n, and MAI decrease with decreasing leaf area. Radiation conversion efficiency, a_c, is smaller at larger LAI because of increased severity and duration of drought. Halving maximum conductance (**G**) slightly increased a_c while doubling the stomatal sensitivity to evaporative demand (**D**) had little effect. Numbers in brackets are % of maximum. These data are based on long-term average monthly rainfall (629 mm yr^{-1}) and potential evaporation (1373 mm yr^{-1}) and a sandy clay loam soil (depth 3 m) that holds a total of 820 mm of water of which 350 mm is available above a soil moisture potential of −1500 kPa.

LAI	3	3	3	3	2	1
Treatment	Irrigated	Rainfed	Rainfed + **D**	Rainfed + **G**	Rainfed	Rainfed
Φ_n (MJ m^{-2} yr^{-1})	4998	4998	4998	4998	4148	2701
E_T (mm yr^{-1})	927	456	456	456	425	380
a_c (g C MJ^{-1})	1.13 (63)	0.67 (37)	0.67 (37)	0.73 (41)	0.80 (44)	1.09 (61)
ε	0.42 (60)	0.41 (59)	0.40 (57)	0.41 (59)	0.41 (59)	0.41 (59)
MAI (m^3 ha^{-1} yr^{-1})	32.0 (33)	18.0 (19)	17.5 (18)	19.5 (20)	18.1 (19)	15.8 (16)

I concluded that, on average, the effect of temperature on the metabolism of photosynthesis and respiration are equally responsible for at least half of the reduction in growth in well-watered, large leaf area stands of *E. globulus* in W.A. Large evaporative demand increases the risk of drought and, especially when combined with drought, further reduces growth. Prolonged periods of slow growth result in reduced leaf area which limits future productivity. There is little scope to improve productivity on marginal sites because of the limitations to growth imposed by temperature, evaporative demand, rainfall and soil type. Reducing leaf area by thinning or wider initial spacing would decrease the severity of drought but reduce productivity. However, slower growing but less drought-stressed trees should be less susceptible to diseases or pests such as *Eucalyptus* longhorn borer (*Phoracantha spp.*) that may ultimately cause stand death.

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Physiological responses to nitrogen application of plantation *Eucalyptus globulus*.

Ingrid Krockenberger, Don White, Richard Bell and Bernie Dell

Nitrogen affects plant growth in two ways - by influencing leaf area and by affecting photosynthetic capacity. Improved nitrogen nutrition results in greater proportional allocation to above-ground biomass, and larger and more numerous leaves. Leaves respond to increased nitrogen availability by greater partitioning of nitrogen to the photosynthetic apparatus relative to other leaf components. Thus improved nitrogen status resulting in greater leaf area for light interception and a greater capacity for carbon assimilation per unit leaf area, potentially leads to a greater subsequent yield.

Application of nitrogen to glasshouse grown *Eucalyptus globulus* seedlings have been reported to increase leaf nitrogen concentrations (eg. Sheriff 1992, Shedley *et al.* 1995) and carbon assimilation rates (eg. Sheriff and Nambiar 1991). However, increased foliar concentrations and photosynthetic capacity following nitrogen application are not always observed in the field (Pereira 1992). Increased nitrogen availability may alternatively lead to an increase in leaf biomass, resulting in dilution of nitrogen within the whole plant, and an increase in shoot/root ratio. The response to nitrogen application on foliar nitrogen concentration and assimilation rates in plantation *E. globulus* trees in my study is shown in Figs. 1 and 2.

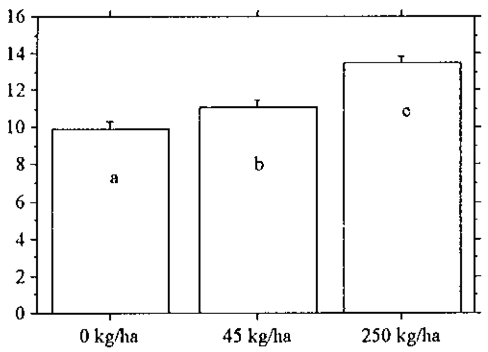

Figure 1. Effect of nitrogen application on foliar nitrogen concentrations of *E. globulus* trees. (Avery's plantation, October 1999).

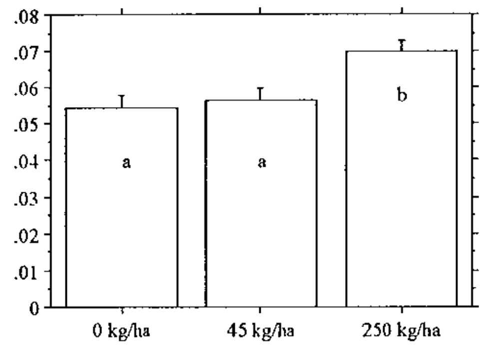

Figure 2. Photosynthetic response in *E. globulus* trees to nitrogen application. (Avery's plantation, October 1999).

As CO_2 deficiency is the most common yield-limiting factor at saturating light, it is possible to identify other constraints when CO_2 deficiency is eliminated. Measurement of photosynthesis at increasing CO_2 concentrations is used to demonstrate the relationship between assimilation rate (A) and internal CO_2 concentration (c_i), known as an A/c_i curve. The effect of nitrogen application on this relationship in field grown *E. globulus* trees is shown in Fig. 3.

The initial slope is where CO_2 limits rate of functioning of the photosynthetic enzyme, Rubisco . The curve plateaus when CO_2 is no longer limiting to the carboxylation reaction and the rate of regeneration of the CO_2-acceptor molecule, RuBP, now limits the activity of Rubisco. Improved nitrogen nutrition (Fig. 3) resulted in increased activity of Rubisco, due to greater investment of foliar nitrogen in the assimilatory apparatus .

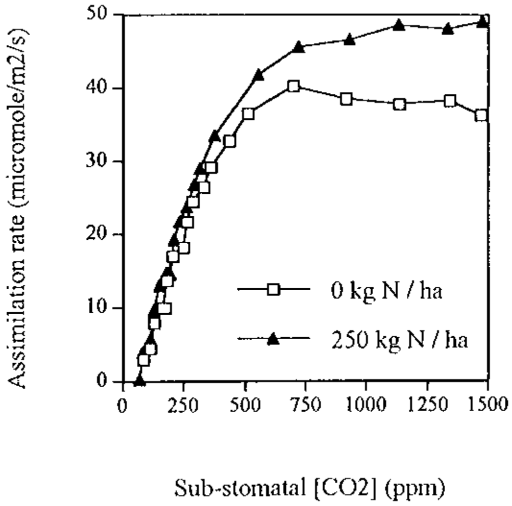

Figure 3. A/c_i curves for two *E. globulus* trees grown at different levels of nitrogen application.
(Avery's plantation, September 1999).

An inevitable consequence of CO_2 uptake is the loss of water vapour via the stomata. Therefore factors which influence photosynthetic activity affect the efficiencies of use of transpired water in assimilating carbon. Water use efficiency or instantaneous transpiration efficiency (TE) can be defined as the ratio of carbon assimilation rate (μmol CO_2 m^{-2} s^{-1}) and transpiration rate (mmol H_2O m^{-2} s^{-1}), measured at the same time at saturating light. Instantaneous transpiration efficiency improved with nitrogen application in plantation *E. globulus* trees in my study, but only at the high level of applied nitrogen (Fig. 4).

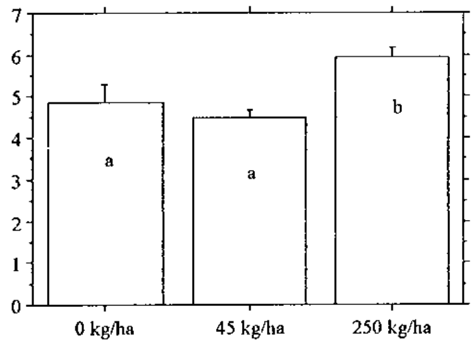

Figure 4. Effect of nitrogen application on instantaneous transpiration efficiency (TE).
(Avery's plantation, September 1999).

During this workshop, I will be presenting some preliminary results of my investigation of leaf scale and tree scale physiological responses to different levels of nitrogen application with the development of water stress in plantation *Eucalyptus globulus*. My principal and initial study area is the Scott River plantation known as "Avery's" by the collaborative partners. Eventually, my study will extend to plantations undergoing greater water stress .

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SILVICULTURE MANAGEMENT OPTIONS FOR *E. globulus* PLANTATIONS

J. F. McGrath, Conservation and Land Management, Locked Bag 104, Bentley Delivery Centre, WA 6983

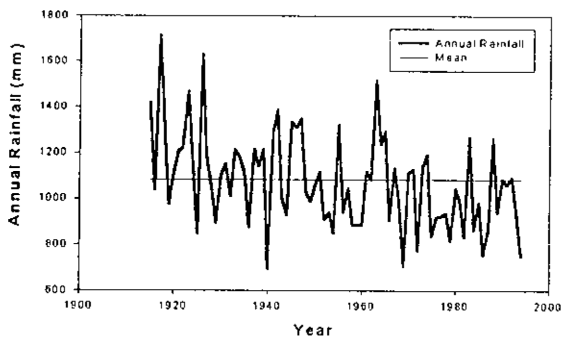
Summary

The markedly seasonal rainfall distribution coupled with periodic droughts in southern Western Australia provides a challenging environment in which to grow plantations. However the success of the softwood plantations across a wide climatic range in this region indicates that is possible to successfully manage plantations in this environment. A range of silvicultural strategies is available to enable managers to match the water demand by plantations to the available water supply.

Background

Drought is considered to occur when rainfall is below the 10th percentile for the period of measurement (Anon 1989). Drought periods or single drought years occur frequently in southern WA, for example consecutive drought periods of between 2 and 4 years occurred five times in the 40 year period from 1950 to 1989 (Figure 1). Tree mortality is much greater in consecutive dry periods than in single drought years (McGrath et al 1991).

Figure1 Annual rainfall for Kirup (1915-1994)



The severe constraint on tree growth in WA due to the annual summer drought and the periodic droughts when winter rainfall is lower than normal has been recognised since at least the 1950's when mortalities were reported in *Pinus pinaster* plantations growing on the Swan Coastal Plain (Butcher & Havel 1976). Periodic droughts during the 1960's led to the development of early and intensive thinning regimes for softwood plantations in WA (Butcher & Havel 1976, McKinnell 1971). The reduction in stand density has the dual effect of reducing the demand for water and also increasing the annual recharge of the soil water store (Butcher 1977, Myers and Talsma 1991).

These silvicultural systems resulted in reduced water stress during summer and hence lower mortality in dry periods and also led to the growth being concentrated on fewer high quality trees. This had the benefit of shortening the rotation length. Generally the lower water use of the thinned stands results in lower overall production than from fully stocked stands.

Silvicultural Options

Options for managing the level of water stress experienced by plantations include using lower planting densities (including strip planting), control of weed competition, thinning of stands and fertilization.

While thinning has not been used silviculturally in bluegum plantations the extensive experience and trial work in softwood plantations indicates that thinning will reduce water stress in plantations (Figure 2). The duration of the relief of water stress depends on how rapidly the leaf area of the thinned stands returns to that of the unthinned stands (or the leaf area prior to thinning). The rate of this recovery can be dependent on nutrient supply. Where the nutrient supply is restricted then leaf area and water stress remain low. When the nutrient supply is high then the recovery of leaf area and hence water stress is more rapid (Figure3)

Figure 2. Influence of thinning on seasonal pre-dawn leaf water potential three years after thinning at Myalup WA. Showing the reduction in water stress in thinned stands.

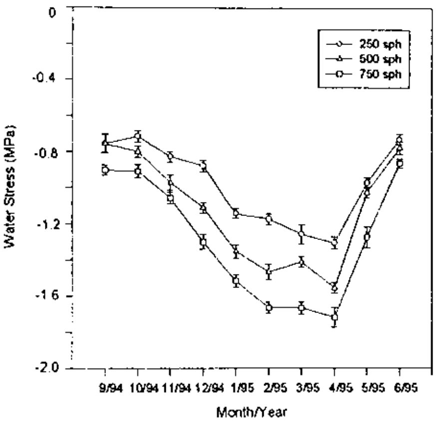
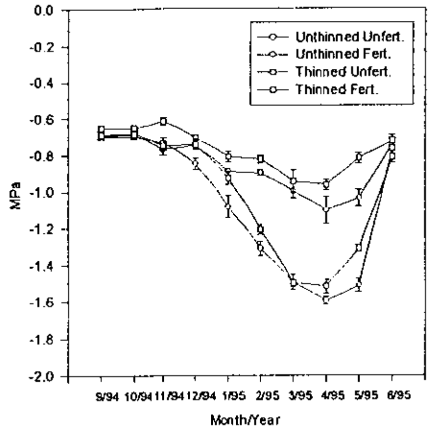


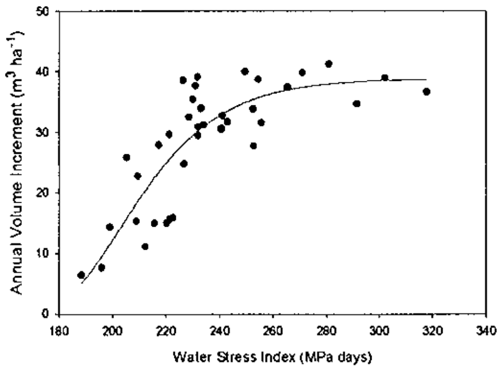
Figure3. Influence of thinning and fertilization on seasonal leaf water potential after eight years for *P.radiata* at Busselton WA. Shows the increase in water stress in both fertilized treatments.



Perhaps paradoxically, under water limited conditions increased water stress was positively related to increased growth (Figure 4). This demonstrated that maximum growth occurred when the available water was fully utilized as indicated by the relationship between yield and water use proposed by Passioura (1977) (Eqn 1). Unless all available water is used then growth will be below the site potential, The aim of silvicultural management is to maximize growth without exposing plantations to the risk of severe water deficit.

Yield =	Water Used	x	Water Use Efficiency	x	Harvest Index	**(Eqn 1)**
m^3 =	(mm)	x	$(m^3\ mm^{-1})$	x	$(m^3\ m^{-3})$	

Figure 4. Relationship between annual volume increment ($m^3\ ha^{-1}\ yr^{-1}$) amd annual Water Stress Index (MPa days). Showing the increase in growth with increasing water stress in a water limited environment



Reduced planting density has been suggested as an effective method of reducing water stress and hence reducing the risk of mortality from drought. The extent of this effect will depend on the rate at which the trees grow and hence reach canopy closure. In dry environments this may be a viable way of reducing the risk of severe water stress hence the risk of drought related mortality. Planting trees in strips is an alternative way to reduce the overall tree density and hence water use. This arrangement of trees across the landscape has been advocated as a way of integrating trees into agricultural systems (Shea et al 1993). Strip planting may well be the most effective way of balancing the risks of high water use in areas with marginal rainfall. The trade off in these systems where water stress is lower is lower production

Similarly, control of weed competition increases the availability of water to trees and results in increased yield. Under the growing conditions experienced by *E globulus* on farmland, weed control significantly increases growth in the first two years (R. Fremlin unpublished). Control of weeds in young plantations while important for early growth rates will have little impact on the longer term sustainable growth rates once canopy closure has occurred, as growth is determined by annual rainfall once the stored soil water has been exhausted. However the early gains in growth from weed control should be maintained for the duration of the rotation.

As outlined by Harper (this meeting) tree growth increased with increasing soil nitrogen where rainfall was adequate, but growth did not increase when the water supply was limited. This is supported by the data from fertilizer trials on a range of sites where large fertilizer responses have been demonstrated on moist sites (Figure 5a) but either no response or tree mortality resulted (Figure 5b) when fertilizer was applied to dry sites. While there are consistent reports of fertilizer reducing water stress, this effect appears to occur at high water availability and under the water limited conditions experienced in WA the overriding influence of fertilization is to increase leaf area and hence increase water demand (Figure 3). Fertilization will only be a useful option on infertile, well-watered sites where the growth rates are below the optimum for the site.

Figure 5a. Resposnse by *E. globulus* to nitrogen application on a moist site (Unicup WA). Shows a positive response to fertilizer where water supply is adequate.

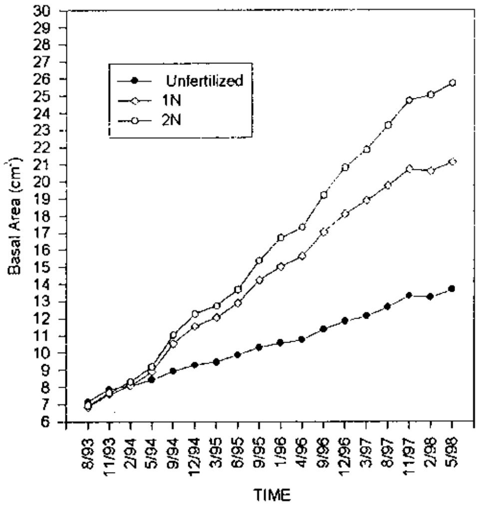
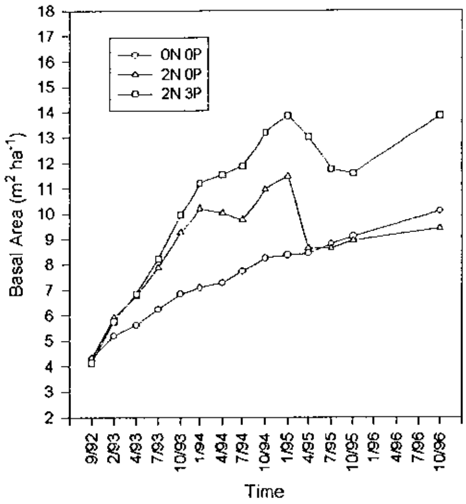


Figure 5b. Response by *E. globulus* to nitrogen application on a dry site (Harvey WA). Shows an initial response to nitrogen followed by mortality when water supply was limited.



Management of water availability in plantations may be more important in the second rotation as the large store of water that had built up under the annual crop and pasture systems in some areas has been depleted during the first rotation. Thus the potential for the development of water stress may increase in the second rotation.

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The Evolution of Systems for Predicting Site Productivity and Risk at Bunnings Treefarms

Tony Smith, Bunnings Tree Farms

It is worth noting that the commercial bluegum industry in Australia is very young. As the industry develops we need to strive for the sophistication which is present in more "mature" silvicultural industries such as in Europe where trees have been grown over many rotations and products and markets are well developed. This paper outlines some of the changes in site selection and site productivity modelling which have occurred at Bunnings Treefarms along our path to "Maturity".

Early days

In the 1980's many of the plantations established by Bunnings treefarms were on ex-bush sites in the Manjimup – Northcliffe region. The poor performance of most of these sites taught us our first lesson in site selection – the importance of nutrition. Following this experience site selection focused on ex-pasture sites with a fertiliser history of at least 5 years.

As more sites were planted it became possible to use early inventory results to guide site selection. A couple of thousand trees were felled across the estate to develop a volume function, and a yield model was developed to "grow-on" inventory volumes. A simple chart was developed which listed growth rates according to rainfall and soil type. The soil type was determined by making an observation of surface soil texture (e.g. sand, loam, and gravel).

Response to drought deaths

The drought deaths of 1994 demonstrated the importance of determining rainfall and depth to rock or hardpans when selecting land. Following the 1994 summer, prospective treefarms were drilled before being accepted. While this improved our ability to recognise risk factors associated with drought death and exclude high-risk areas from future plantations, it did not improve our ability to predict growth rates on areas we accepted as plantable.

Establishment of Permanent Sample Plots

In the summer of 1994/5 the first 70 in a series of over 300 permanent sample plots (PSP's) was established over the plantation estate (approximately one per 50 ha). The purpose of the plots was to derive accurate growth curves and relate these to site factors. These plots have been established every year for six years and now cover the range of soil / landscape /climate types in which Bunnings Treefarms operates. For each plot, the landscape and soil physical and chemical properties are described in detail using backhoe pits and drilling. Tree volumes are measured every 2 years. Since their establishment, the PSP plots have been invaluable in the development and ongoing improvement of site productivity modelling.

Development of a statistical model (SITEPROD)

By 1996/7 the oldest plots in the PSP series were 6 – 7 years old and had 2 measurements. Dr Chris Shedley and Dr Mike Battaglia used the PSP site data combined with growth data to determine the relative importance of soil and climate factors in determining growth rates. Decision Tree analysis was used to determine the most important variables influencing tree growth. These were

- The ratio of mean annual rainfall to mean annual evaporation (P/E)
- Available soil depth
- Salinity and
- Nutrient status

Generalised linear modelling was used to develop and test a multi-variable predictive model. This model (based on the four variables above) was then adopted for the determination of MAI before planting.

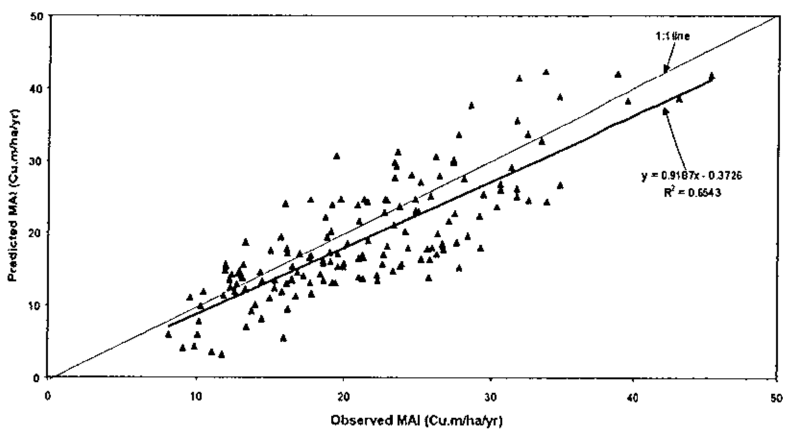
Modification of Dr. Mike Battaglia's Mechanistic Model (PROMOD)

PROMOD has been evaluated in parallel with the statistical model SITEPROD since 1996/7. When PROMOD was first run using PSP data the initial predictions were not good (r^2 – 0.4). After modifications were made to account for salt and hardpans, the predictive ability improved (r^2 = 0.7).

Improvements to the BTF Growth model

Both SITEPROD and PROMOD use MAI at age 10 to rank the performance of sites. This is determined for the older PSPs by "growing on" trees aged 6 to 9 years. By 1998 the oldest PSPs were 8 to 9 years old and had three measures. It became clear that the predictive ability of site productivity modelling had become limited by the ability of the current growth model to "grow-on" the trees rather than the ability of SITEPROD or PROMOD to accurately integrate soil/climate factors and then scale sites according to productivity. The PSP data were used to develop an improved growth model that more accurately reflected the range of bioclimatic regions encompassed in the expanding BTF estate. An example of the latest PROMOD runs using the new model is given in Figure 1 below.

Figure 1: Comparison of Observed Vs Predicted MAI using PROMOD



Ongoing challenges and developments

It has been important to immediately transfer research findings to management, foresters and land officers within Bunnings and continually update land leasing and rent payments according to new information. Harvest yields confirm the accuracy of current predictions. The latest project to further improve yield prediction will be to improve the taper function used to estimate tree volumes. Data management systems are being developed to annually update site productivity models, growth and volume functions as new PSP, inventory and harvest data becomes available. Representative sets of PSPs are being selected to

- Grow on beyond current harvest age
- Re-measure for second rotation.

Involvement in collaborative research such as this productivity and drought risk project are seen as crucial to the ongoing improvement of operations at BTF and the industry as a whole.

BALANCING PRODUCTIVITY AND DROUGHT RISK IN BLUE GUM PLANTATIONS

Stuart Crombie (CALM), Don White (CSIRO) and Tony Smith (Bunnings Tree Farms)

Introduction

Better site selection, management guidelines and growth predictions are required by the blue-gum plantation industry in south-west WA. This is especially so as the industry matures and management intensifies to achieve the greatest possible commercial return.

Presently, plantation location and management is based on empirically developed guidelines. Data for these guidelines has been obtained largely from single or repeated surveys of stands planted and managed as part of larger commercial operations (*e. g.* Crombie, McGrath, Harper and Smith in earlier talks at this workshop). While, the diversity of biophysical attributes (eg. climate, soil type and depth, fertility, site preparation and stand age) of sites incorporated in these surveys has allowed general rules to be developed for site selection it is very difficult to identify or predict the effect of a single variable on tree or stand performance from this data.

Regional surveys and mensurational data have identified water availability (moderated by rainfall, evaporation and soil type and depth) and fertility as two of the major determinants of stand growth on sites otherwise suitable for plantations. While fertility is amenable to management amendment by addition of the appropriate nutrients management of the finite supply of rain water for maximum return is much less well understood. Fertility and water supply also interact strongly so that changing one is very likely to affect another (eg. fertilizing a stand will generally increase leaf area and hence stand water demand).

A way of generalizing tree and stand growth in response to changes in one or more specific factors is required.

A standard ANOVAR type of experiment in which a number of treatments are varied is one possible solution. Estimates of the growth of a commercial stand can be extrapolated from such experiments for similar sites and stands. However, this approach is limited as results cannot be confidently extrapolated beyond the types of sites, climates and stand characteristics under which the original experiment was conducted.

Process-based growth models offer a better way extrapolating from a limited number and range of experiments to the wider range of sites and conditions found across the plantation estate. Process-based models also offer a means of anticipating the results of management options without the expense and losses associated with experimental testing.

ProMod, 3-PG and BIOMASS are all process-based growth models which may be applicable to the plantation situation. A key tenet of these models is that growth is a function ultimately of radiation interception, itself largely determined by leaf area. Leaf area is adjusted in response to increasing age or nitrogen uptake (increases leaf area) or water deficit and thinning (reduces leaf area).

Obtaining the data to conduct ANOVAR-type analyses or to run and test process-based growth models is time consuming and expensive. It makes sense therefore to combine the efforts of parties with a stake in the bluegum plantation industry to increase the amount and intensity of data collection from across the potential bluegum plantation range.

Accordingly, four stakeholders in the bluegum plantation industry in WA have combined their resources to conduct a single large experiment to test the effect of nitrogen fertilization and stand density (two of the main determinants of stand productivity) across a representative range of climatic types in the south west of WA.

Contributors to the work described here are Bunnings Treefarms, The Department of Conservation and Land Management of WA, CSIRO Division of Forests and Forests Products and Timbercorp.

Balancing Productivity and Drought Risk in Blue Gum Plantations

The experiment consists of a combined Thinning x Fertilizer trial repeated on five sites representative of the range of evaporation and rainfall in the potential blue gum growing area of WA. Other selection criteria were that soils were likely to be nutrient deficient (to improve outcomes from the nitrogen rates experiment) and penetrable soil profiles were sufficient to store all winter rainfall (ideally >9 m deep).

Objectives:

a) Establish quantitative relationships amongst soil depth, climate, leaf area index, water use, growth and the development of water stress in tree farms across a range of site qualities.

b) Develop from this data a prediction of the highest leaf area index which is can be carried on a given site.

c) Generalize the empirical model developed in b) to a general physiological process model (ProMod) which will be capable of predicting maximum sustainable leaf areas and productivities for a larger range of potential planting sites and possibly species.

Treatments

Treatments applied were (Table 1);

nitrogen (0, 45, 125, 250 and 500 kg ha^{-1} $year^{-1}$)
thinning (nominally 1200, 600 and 300 stems ha^{-1})

Four rainfall and evaporation combinations were considered as experimental treatments;

high rainfall/low evaporation
low rainfall/low evaporation
low rainfall/high evaporation and
medium rainfall/medium evaporation.

All treatments were initially applied to two year old plantations in spring of 1998 and 1999. Irrespective of treatment year, plantations were two years old when treated.

Each years' nitrogen allocation was split into two equal lots with a half being applied after the start of winter rains in autumn and the remaining half after the last rains in spring.

To limit workloads, a full factorial of nitrogen application x thinning was not attempted. Instead nitrogen treatments were applied to a subset of thinning treatments.

Measurements:

Bi-monthly measurements are being made of

DBHOB and height (5 trees per plot, stratified by size)
Leaf Area Index (LiCor2000)
Plant water status (dawn water potential by Scholander Bomb)
Soil moisture content (neutron moisture meter to 9m nominal depth)
Annual measurements of height and diameter of all sites and soil and leaf nitrogen status are made in August/September.

Plot locations and local isohyets are shown in Figure 1. Details of stand condition at establishment and responses in the first year of the experiment will be discussed.

Figure 1. Map of South Western Australia showing the location of experiments.

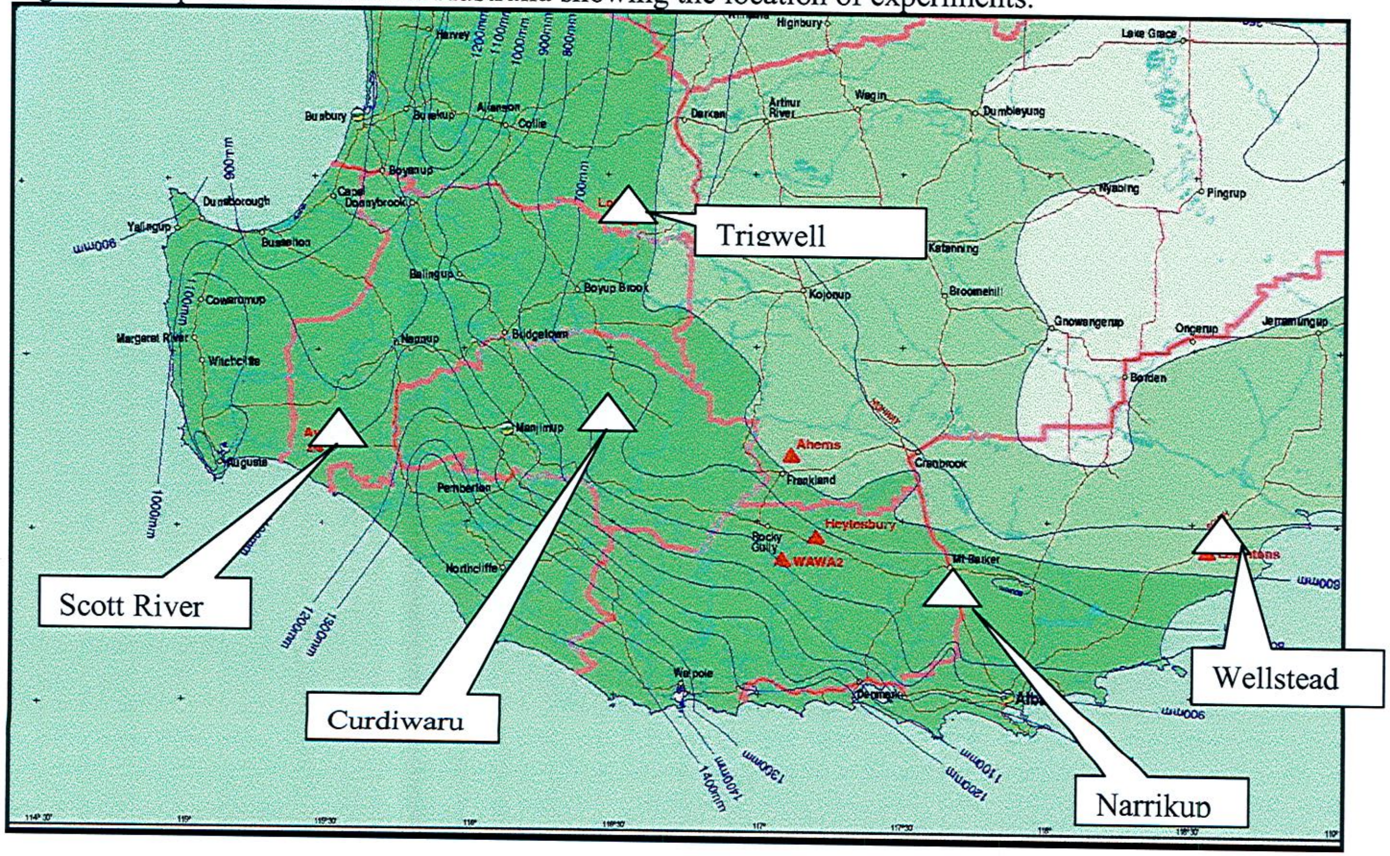


Table 1a. Fertilizer and Stand Density Combinations.

		STAND DENSITY (STEMS Ha^{-1})		
		1200	600	300
NITROGEN (Kg Ha^{-1})	0		a	
	45			
	125			
	250		a	
	400			

a – ommitted from Curdiwarup and Narrikup

Table 1b. Climate contrasts between sites.

	EVAPORATION		
RAINFALL	HIGH	MEDIUM	LOW
HIGH			SCOTT RIVER (1998, 1100, 1290)
MEDIUM		NARRIKUP (1999, 750, 1460) CURDIWARUP (1999, 800, x)	
LOW	TRIGWELL BRIDGE (1998, 650, 1460)		WELLSTEAD (1998, 550, 1540)

Numbers in brackets are (Year of treatment, annual rainfall, annual evaporation)

"Managing productivity and drought risk to blue gum plantations in a Mediterranean climate in south western Australia"

Field Tour – November 10th 1999

Organised by Don White, Stuart Crombie and Tony Smith – Project Scientists

Stop 1, Avery's Tree Farm.

Avery's Tree Farm (Scott River) is one of three sites at which experiments were established in Spring 1998 (trees were planted in 1996). All three sites have a sandy A horizon likely to be N deficient, show evidence of laterite in the top 2 meters with clay sub soils able to store plenty of water. The sites cover the range of climatic conditions in which blue gums are planted in southwestern Australia: high rainfall and low evaporation (Avery's Tree Farm), low rainfall and low evaporation (Leighton's Tree farm, Wellstead) and low rainfall with high evaporation Loton's Tree Farm(Trigwell Bridge). At all sites trees were planted in 1996 at a nominal spacing of 4 m between and 2 m within rows. Other site details are summarised in Table 1.

Table 1. Site descriptions for the three major sites

	Altitude m ASL	Latitude	Longitude	Rainfall mm	Evaporation mm
Avery's[1]	75	34°17′ S	115°29′ E	1082	1287
Leighton's	120	34°35′ S	118°33′ E	591	1350
Loton's	240	33°38′ S	116°34′ E	629	1460

In spring 1998 two experiments were established on each site. A randomised block design was used with some treatments common to both experiments. At each site 3 replicates or blocks were established. All plots were 40 m x 40 m or 10 rows x ca. 20 trees.

The first experiment was a spacing by nitrogen fertiliser trial with 3 stand densities[2] (300, 600 and 1200 stems ha^{-1}) and two rates on N application (0 and 250 kg ha^{-1} y^{-1}) in a factorial design (giving 6 plots per replicate). The second experiment was a nitrogen rate trial with 5 rates of N (0, 45, 125, 250 and 400 kg ha^{-1}) applied to the maximum stand density plots. The 0 and 250 kg ha-1 plots were common with the first experiment giving a total of 9 plots per replicate for a total of 27.

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[1] Avery's, Loton's and Leighton's are, respectively, located near Scott River, Wellstead and Trigwell Bridge. Elsewhere in this booklet they may be referred to by these locality names.

[2] The highest stand density is only approximate. These plantations were established at approximately 1200 stems ha^{-1} and the high stand density indicates only that the plots were not thinned.

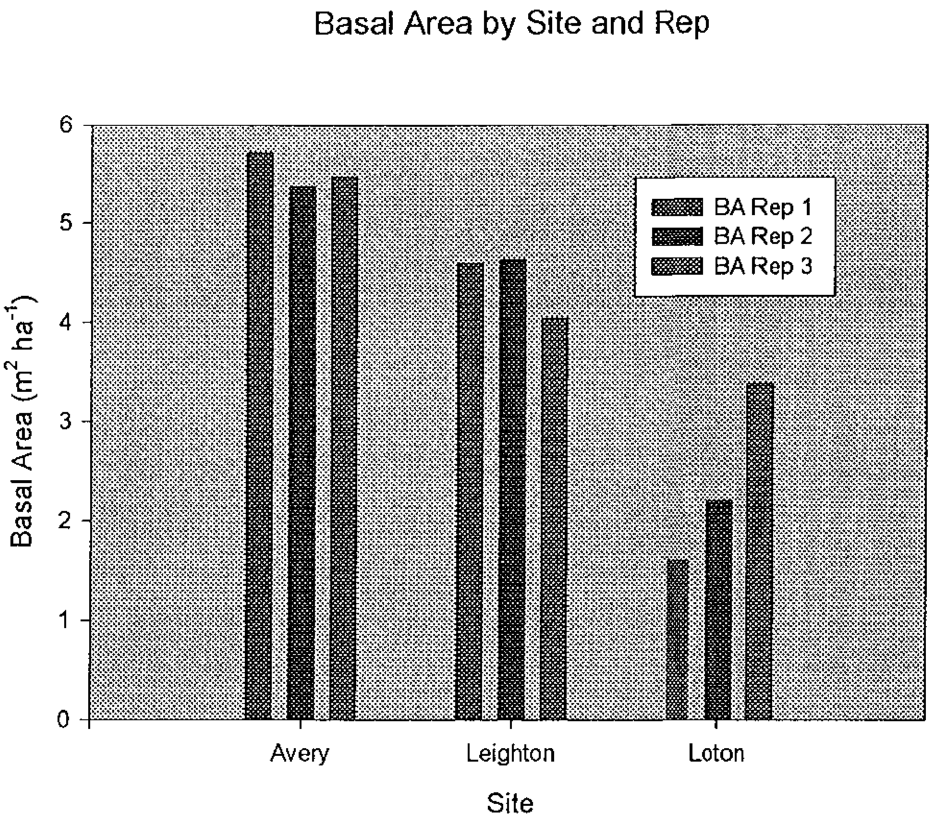


Figure 1. Basal Area at Avery's, Leighton's and Loton's prior to the application of treatments. Basal Area was significantly affected by replicate at Loton's but not at the other sites.

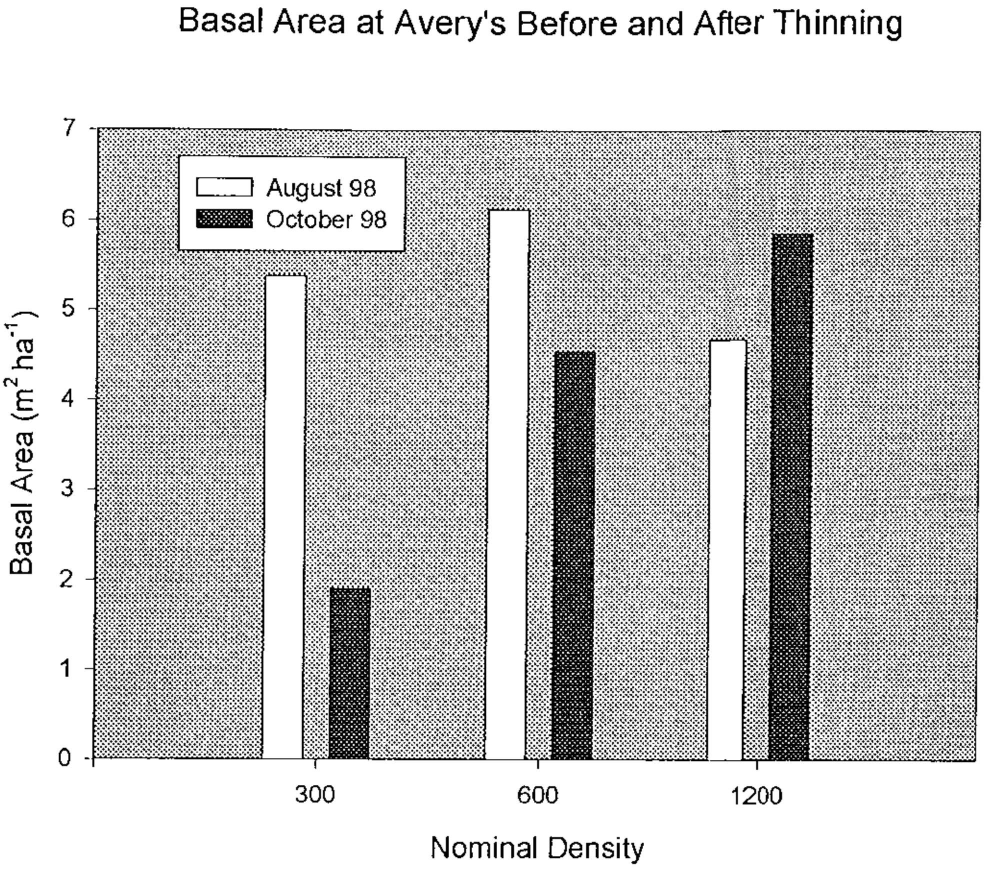


Figure 2. Mean Basal Area for unthinned plots and plots thinned to 300 and 600 stems ha^{-1}. Data shown are for Avery's Tree Farm before (August 1998) and two months after (October 1998) thinning. These data indicate a very rapid growth response to thinning, especially in the 600 stem per ha^{-1} plots.

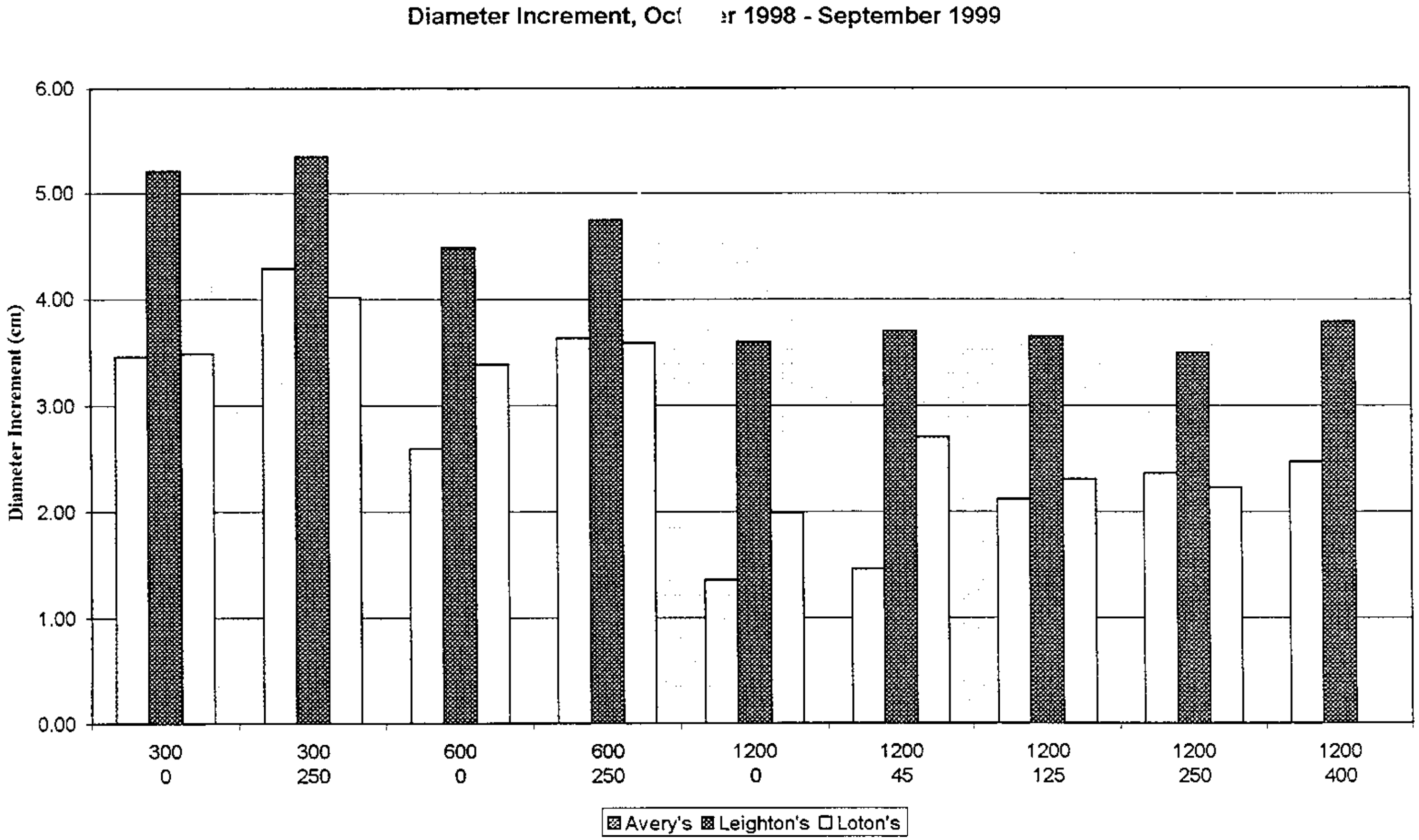


Figure 3. Diameter increment by stand density (300, 600 and 1200 stems ha^{-1}) and rate of N application (0, 45, 125, 250 and 400 kg ha^{-1} yr^{-1}) for Avery's, Leighton's and Loton's Tree Farm. Results: a) N rate trial. Significant N response at Avery's but not at Leighton's or Loton's. b) N x spacing trial. Significant response to N and spacing at all sites.

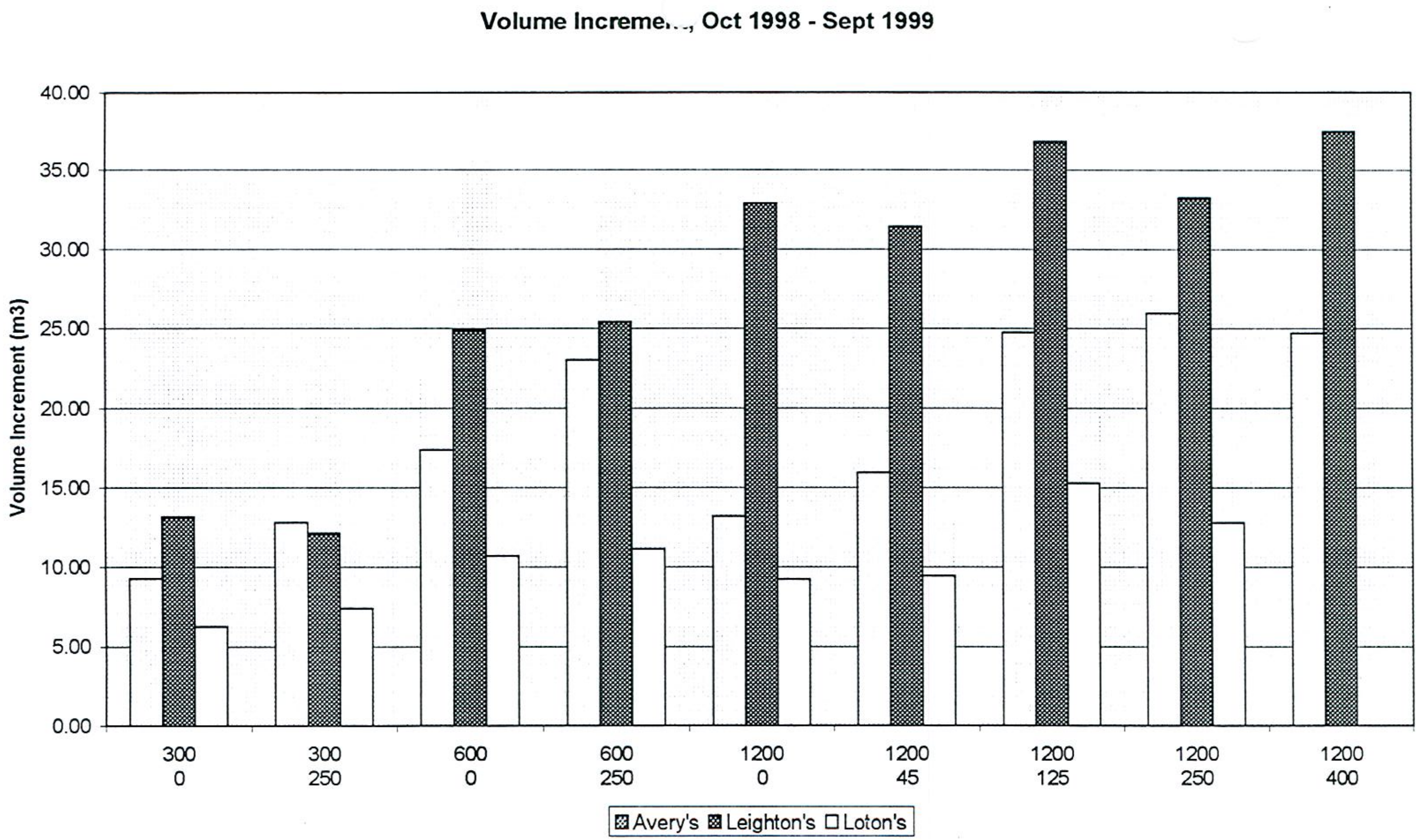


Figure 4. Current annual increment by stand density (300, 600 and 1200 stems ha^{-1}) and rate of N application (0, 45, 125, 250 and 400 kg ha^{-1} yr^{-1}) for Avery's, Leighton's, and Loton's Tree Farm. **Results**: a) N rate trial. Significant N response at Avery's and Loton's but not at Leighton's. b) N x spacing trial. Significant response to N and spacing at all sites.

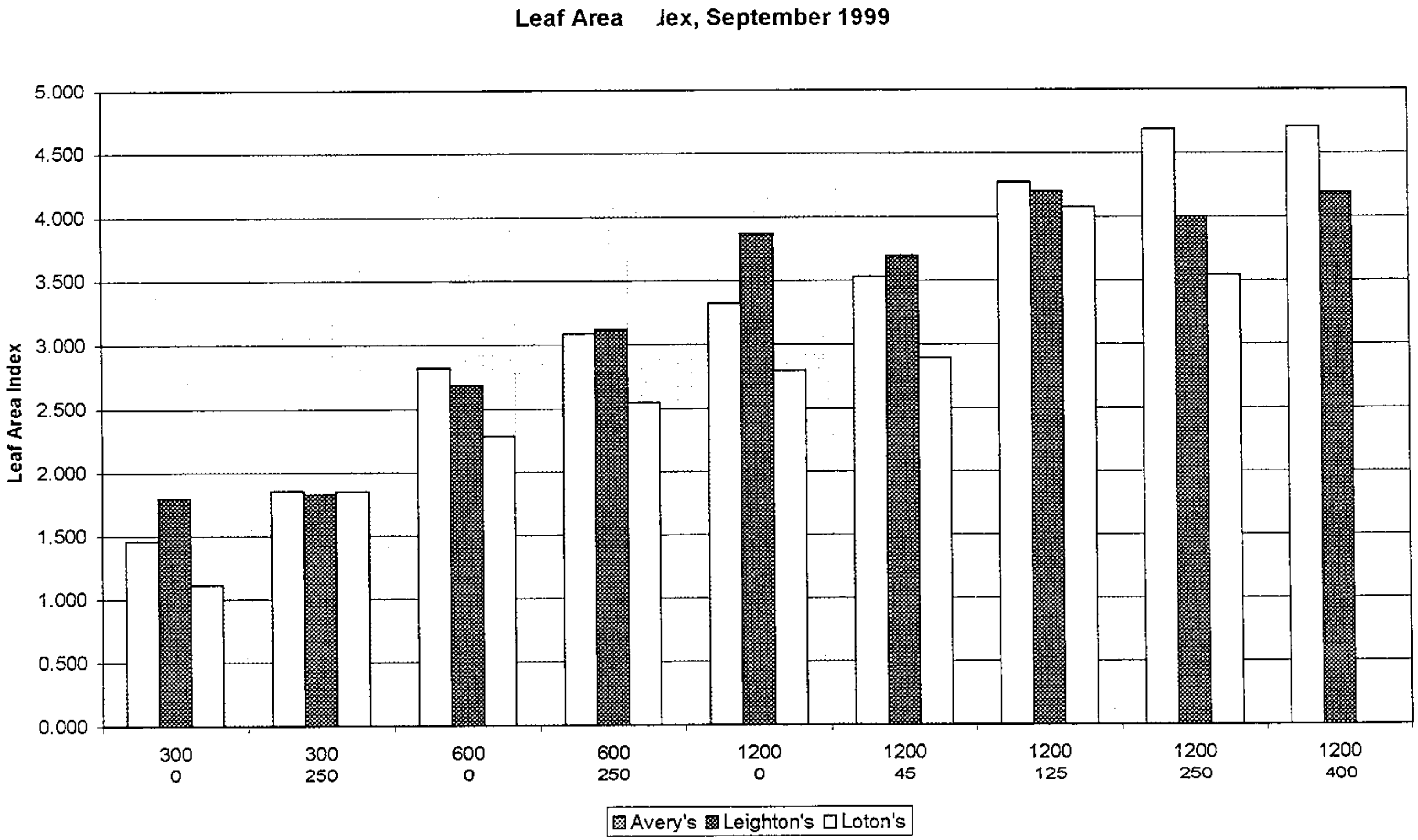


Figure 5. Current leaf area index by stand density (300, 600 and 1200 stems ha^{-1}) and rate of N application (0, 45, 125, 250 and 400 kg ha^{-1} yr^{-1}) for Avery's, Leighton's Tree Farm. **Results**: a) N rate trial. Significant N response at Avery's and Loton's but not at Leighton's. b) N x spacing trial. Significant response to N and spacing at all sites. c) Also note the wide range of leaf area indices generated at each site.

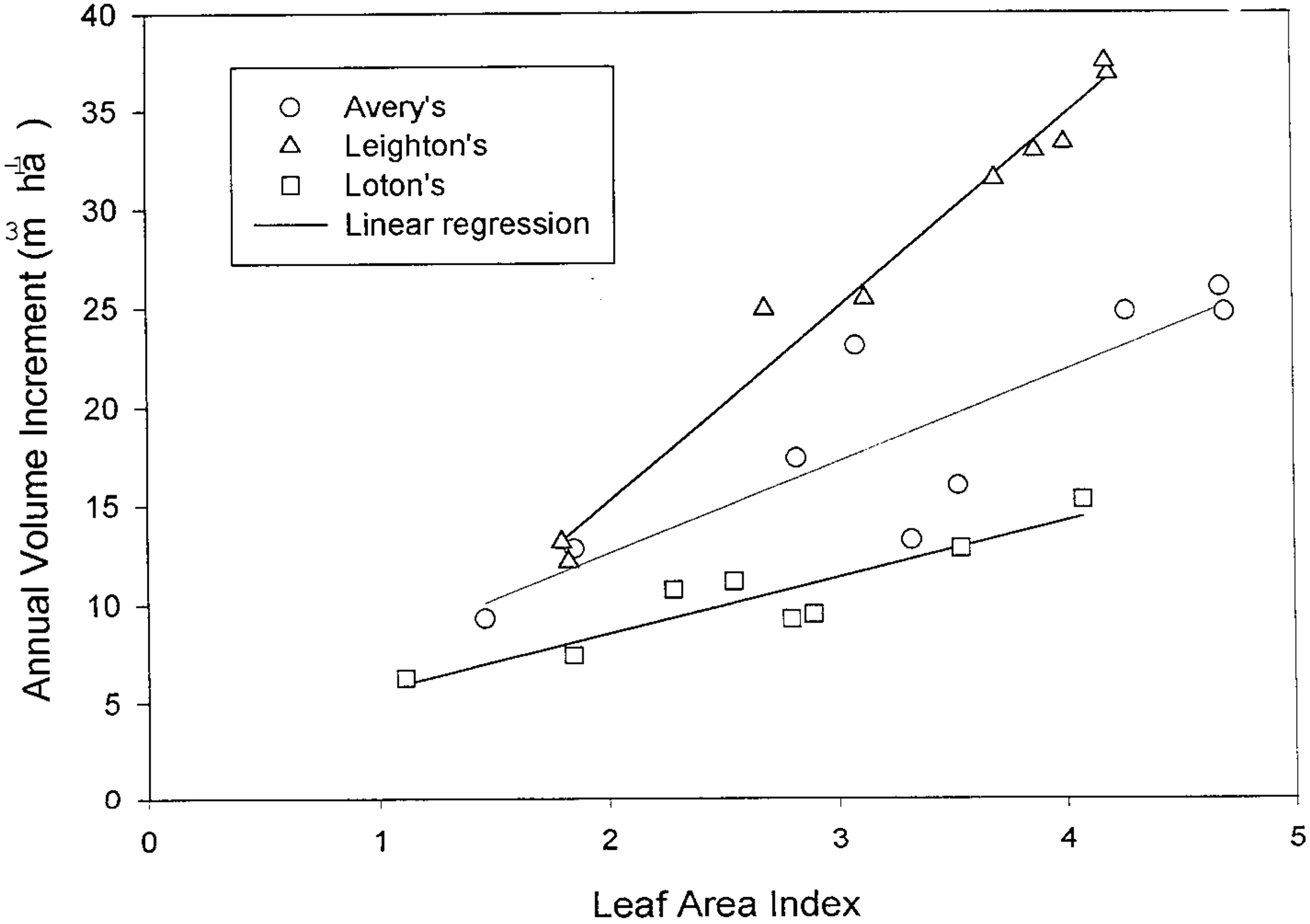
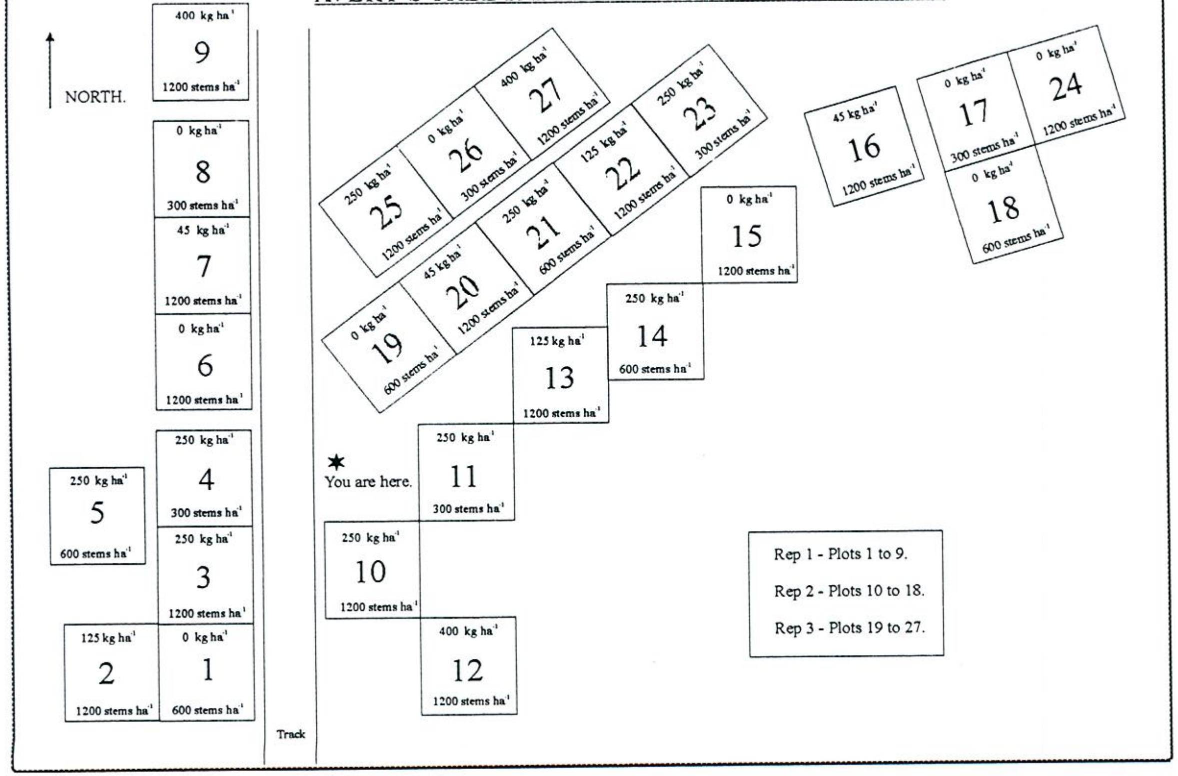


Figure 4. Current Annual Increment as a function of Leaf Area Index for Leighton's, Avery's and Lotons Tree Farms. Linear regressions were highly significant ($p<0.001$) for all sites. The predawn leaf water potential at these three sites were -0.5, -0.9 and -1.1 MPa respectively. Water stress may have been a principal determinant of the slope of these relationships. Inclusion of two additional sites will enable us to develop relationships to predict the parameters of these relationships from, predawn leaf water potential, available soil water fraction and foliar N.

AVERY'S TREE FARM PLANTATION- SCOTT RIVER.



BALANCING PRODUCTIVITY AND DROUGHT RISK IN BLUE GUM PLANTATIONS

Don White, Stuart Crombie, Tony Smith and Ian Bail

CSIRO

CALM DEPARTMENT of CONSERVATION and LAND MANAGEMENT

BUNNINGS TREEFARMS

TIMBERCORP

Objectives

- Establish quantitative relationships amongst soil depth, climate, leaf area index, water use, growth and the development of water stress in blue gum plantations.
- Develop the capacity to predict the leaf area index that is sustainable on a given site.
- Recommend silvicultural options for achieving a sustainable leaf area index and wood production.

Planned Outcomes

- Robust relationships between leaf area index and productivity in a Mediterranean environment as a guiding tool for forest managers.
- Recommendations for maximum sustainable leaf area index of blue gum plantations on specific sites.
- Recommendations on the maximum growth rates possible at a specified risk of drought death.
- Recommendations on fertiliser application and initial spacing for managing leaf area index to optimise productivity at a given level of risk.

Research Approach

- In 1998 experiments were established at three core sites, selected to cover a climatic gradient defined by the difference between rainfall and evaporative demand (Table 1). These experiments were established in 2 year old plantations.
- At each site tree spacing and the rate of nitrogen application were varied to establish plots with a range of leaf area index.
- In 1999 similar experiments were established at two additional sites with intermediate average annual rainfall

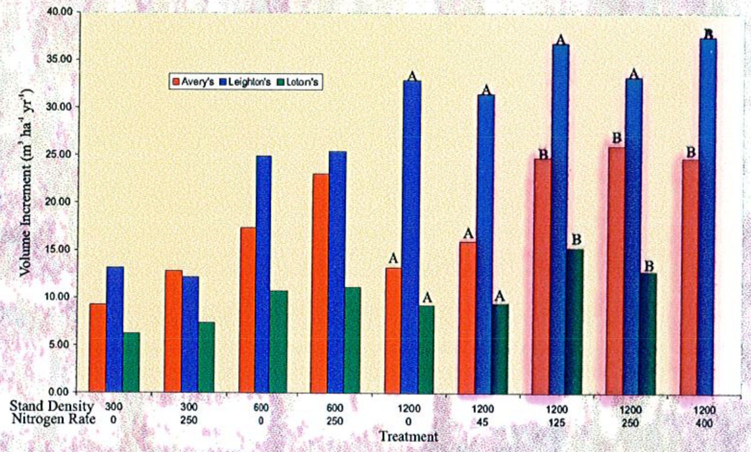
Table 1. Site descriptions for the three major sites

	Altitude m ASL	Latitude	Longitude	Rainfall mm	Evaporation mm
Avery's	75	34°17′ S	115°29′ E	1082	1287
Leighton's	120	34°35′ S	118°33′ E	591	1350
Loton's	240	33°38′ S	116°34′ E	629	1460

- Height and diameter, leaf area index, soil water content to 10 m, pre-dawn leaf water potential and foliar N concentration are measured on a bi-monthly basis.

1. Volume Increment

Current annual increment (CAI, 1998-1999) by stand density (300, 600 and 1200 stems ha^{-1}) and rate of N application (0, 45, 125, 250 and 400 kg ha^{-1} yr^{-1}) for Avery's, Leighton's, and Loton's Tree Farms. CAI was significantly increased by N application at Avery's and Loton's but not at Leighton's. Within sites, treatments with the same label were not significantly different ($p<0.05$).



2. Leaf Area Index

- In September 1999 leaf area index ranged from 1.2 to 4.8 across the three sites. One year after establishing the experiments, plots with a range of leaf areas were established. These will allow us to explore relationships amongst leaf area, productivity, water use, water status and drought risk.
- At each of the three core sites more than 80% of variation in CAI was explained by leaf area index (LAI) alone. The slope of these relationships varied a great deal between sites. This variation was correlated with predawn leaf water potential. Minimum predawn leaf water potential for the measurement period was -0.5, -0.9 and -1.15 MPa for Leighton's, Loton's and Avery's respectively. Similarly specific leaf area for the same sites was 4.94, 4.51 and 3.99 m^2 kg^{-1}.
- As data becomes available for all five sites we aim to predict the slope of the CAI vs. LAI relationship from a few easy to measure site factors.