

Competition for soil water and nitrogen between *Holcus lanatus* L. and young *Eucalyptus globulus* Labill.

by

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A thesis submitted in fulfillment of the
requirements for the degree of
Doctor of Philosophy

School of Agricultural Science, University of Tasmania; and
Co-operative Research Centre for Sustainable Production Forestry
Hobart, Australia

May 2004



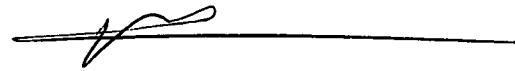
E. globulus age 13 months and *H. lanatus* (November 1997).
Note: sprinkler with spot weed control.

Dedication

This thesis is dedicated to my father, Robert H. Adams,
who fostered my love of trees and forestry from an early age.

Declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution and that, to the best of my knowledge and belief, contains no material previously published, or written by another person, except when due reference is made in the text of the thesis.



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Paul Reid Adams

Abstract

Competition for below-ground resources was investigated between young *Eucalyptus globulus* Labill. (Tasmanian blue gum) and *Holcus lanatus* L. (Yorkshire fog grass) in a plantation in SE Tasmania, Australia. The objectives of the study were (1) to measure the competitive effect of weeds on the growth of *E. globulus* under contrasting levels of soil water and nitrogen availability and (2) to determine the 'critical period' of competition for soil water and nitrogen in a developing stand of *E. globulus*. This information lead to improved understanding of the mechanisms of competition between *H. lanatus* and young *E. globulus*.

A two hectare field experiment was established on a low rainfall (500 mm yr⁻¹), ex-pasture site with a sandy soil of low to moderate fertility. Two levels of both irrigation and nitrogen (N) fertiliser (urea) were applied to provide contrasting soil water and nitrogen levels. A range of periods of weed presence and absence (following the Critical Period method) were used in specific combinations of water and nitrogen availability.

Weedy plots were rapidly dominated by *H. lanatus*, a very competitive grass, that had up to 100% cover and grass biomass production of 9 - 14 t ha⁻¹ one year after planting *E. globulus*. There were strong responses to nitrogen fertiliser in the weedy treatments, but there were only small responses to irrigation, regardless of weed status. Lateral root growth of *E. globulus* was severely restricted by the vigorous development of grass roots that completely dominated the surface soil horizons.

After two years, *E. globulus* height and diameter growth was up to 3 and 4.8 times greater, respectively, in weed-free plots compared to trees growing with grass. Where grass was present, there was no tree growth response to level of irrigation, but diameter was 1.8 times greater due to N-fertilisation, which indicated more severe competition for N in the unfertilised treatment, even though grass growth was also less vigorous in this treatment. Growth recovery after the application of weed control was also slower in the unfertilised treatment, and was influenced by season, with faster tree recovery following spring compared to autumn weed removal. Although there was no significant growth response to irrigation, the response to nitrogen in weedy treatments was stronger with the higher level of irrigation indicating a water by nitrogen interaction in the surface soil.

The critical period for grass control at this site was from planting to age 20 months to avoid growth reduction caused by grass competition. There was no early period after planting when weeds could be tolerated by the young eucalypts. Most of the growth suppression occurred during the first 12 months, while maximum diameter growth (80%) was approached after approximately one year of weed control. These effects on growth were still evident 4.4 years after planting.

Grass growth reduced surface soil water content during the first year and mild to moderate tree water stress ($\psi_{\max} < -0.55$ MPa) occurred on a number of occasions during the first 18 months of growth. There was high availability of water for plant use in the top 1 m of soil for most of the period, reflecting the overriding influence of the shallow water table at the site. However, in one block on the drier part of the site,

available water was reduced by up to 80% due to grass presence during the first year, and this area exhibited the greatest degree of water stress.

Soil nitrogen was strongly affected by grass presence, with NH_4^+ concentrations higher under grass, while NO_3^- was lower. Rates of nitrification and leaching were high in the surface soil in weed-free conditions. The application of nitrogen fertiliser (N_{High}) caused rapid increases in the concentrations of NH_4^+ and NO_3^- in soil solution especially in weed-free plots, with greater increases after spring compared to autumn application. Both NH_4^+ and NO_3^- concentrations decreased to low values (<0.10 mM) during the first winter after planting (age six to nine months) except in N_{High} weed-free plots. Thereafter, mineral N concentrations were variable with wide fluctuations that were probably related mostly to season, temperature, moisture and grass presence.

Concentrations of N in foliage reflected levels of soil available nitrogen. Trees grown with grass had half the foliar nitrogen concentration of trees growing under weed-free conditions early in the first year. Concentrations increased following the addition of nitrogen fertiliser, and were equivalent to those growing under weed-free conditions by the end of the first year. The increased nitrogen status did not compensate for the lost growth. Vector analysis demonstrated that the competitive effects were mediated by water and nitrogen.

Evidence from this research suggests that competition between *H. lanatus* and young *E. globulus* at this site was mainly for nitrogen, and to a lesser extent soil water during the first 12 – 18 months of tree growth. Where water was non-limiting in

surface soil, competition for nitrogen was high, while in the drier part of the site, both water and nitrogen were limiting in the presence of grass. The use of the critical period method has provided a definition of the period when grass should be controlled to avoid *E. globulus* growth losses and has indicated the potential importance of an interaction between nutrient and water availability to the expression of the response.

This research indicates weed control requirements for *E. globulus* on ex-pasture sites can be determined on the basis of site fertility and moisture regime. In this way operations can be tailored on a soil and site basis. The trade-off will be increased management complexity, however, improved knowledge and understanding of these factors enhances more effective and efficient plantation weed management. The extension of this approach to other species (weeds and trees) is also possible.

Publications arising from this thesis

Conference papers:

Adams, P. R., Smethurst, P. J., Beadle, C. L. and Mendham, N. J. (1998) Mechanisms of grass competition in a young *Eucalyptus globulus* plantation. Eds: Wagner, R. G. and Thompson, D. G. Third International Conference on Forest Vegetation Management: Popular summaries. August 1998. Ontario Forest Research Institute. Forest Research Information Paper No. 141. 35-37.

Adams, P. R., Smethurst, P. J., Beadle, C. L. and Mendham, N. (2002) Effects of soil water and nitrogen on grass suppression of young *Eucalyptus globulus*. Eds: Spafford Jacob, H., Dodd, J. and Moore, J. H. 13th Australian Weeds Conference. Sheraton Perth Hotel, Perth, Western Australia. Council of Australian Weed Science Societies. 43-46.

Journal papers:

Adams, P. R., Beadle, C. L., Mendham, N. and Smethurst, P. J. (2003) The impact of timing and duration of grass control on growth of a young *Eucalyptus globulus* Labill. plantation. *New Forests*, 26 (2): 147-165.

Adams, P. R., Beadle, C. L., Mendham, N. and Smethurst, P. J. The use of vector analysis to determining the effects of grass competition on early nutrition and growth of *Eucalyptus globulus* Labill. In preparation.

Acknowledgements

Sponsorship, cooperation and assistance from Land & Water Australia, University of Tasmania School of Agricultural Science, and forest growers: Forestry Tasmania, Norske Skög, (formerly Fletcher Challenge Paper), Gunns Ltd (formerly Boral Timber Tasmania, and North Forest Products) and Grand Ridge Plantations (formerly Australian Paper Plantations) is gratefully acknowledged.

I would like to thank

- My three supervisors: Drs Neville Mendham, Philip Smethurst and Chris Beadle, who supported and provided guidance through this project and are a major reason for the success of the project.
- Mr Bill Neilsen (Forestry Tasmania), Ms Sandra Hetherington (Norske Skög), Mr Peter Norton and Dr Greg Holz (formerly of Gunns Ltd) and Dr Silvia Pongracic (formerly of Grand Ridge Plantations) initiated the PhD project and provided friendship and support throughout.
- Students and staff from CSIRO Forestry and Forest Products and the Cooperative Research Centre for Sustainable Production Forestry provided fieldwork and site management assistance which is gratefully acknowledged. Particularly, Mr Dale Worledge for helping to establish the experiments and for site management especially irrigation; Ms Joanne Dingle, Mr Rick Hand (deceased); Ms Ruth Osborne, Mr Keith Churchill and Ms Sue Baker for much assistance in experiment establishment and maintenance; and many others for helping with the large amounts of fieldwork involved. Ann Wilkinson for advice and assistance in the lab; Ms Jean Richmond for help with finances and always a time for a chat;

Ms Judy Sprent for help and support in library matters; and Mr Phil Coles for helping me with computer hardware and systems support. Dr David Ratkowski, Dr Steve Candy and Dr Luis Apiolaza for assistance with various statistical issues. Maria Cherry for proof reading the manuscript. Dr Zoltan Lukacs, Dr Martin Moroni and Dr Tara Simmul for their friendship and encouragement during the study; and Mr Sven Ladiges for plenty of discussion and argument on a wide range of issues.

- Mr Robert and Mrs Betty Morey of 'Flexmore Park', Penna, very accomplished farm foresters who were most helpful both with time, labour, equipment and advice. Also to Mr Don Evans for much help with fieldwork.
 - Impact Ltd provided fertilisers for the experiment.
 - Department of Primary Industries, Water and Environment, and Mr Dennis Morris from the Tasmanian Herbarium, for allowing me to use illustrations of the two weed species *H. lanatus* and *A. vulgaris*.
 - Mr Robert Boardman (formerly of Forestry SA) who encouraged me to apply for the PhD scholarship and who has been a constant source of inspiration for me.
 - My father, Robert Adams, for encouragement, support and a constant belief in my abilities.
 - To Carolyn, for her wonderful support, encouragement, and valuable comments.
 - And finally to Gail and our three beautiful daughters Georgia, Olivia and Chloe.
- The hard work and persistence has finally paid off.

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1. Introduction

1.1 The problem

Grasses and herbaceous broad-leaved weeds are widely encountered during plantation establishment and constitute a major impediment to successful early growth and development of tree crops (Knowe *et al.* 1985, Boomsma and Hunter 1990, Richardson 1993, Savill *et al.* 1997). Interference from these weeds can range from significant suppression of growth to widespread mortality, and cause reduced productivity throughout the rotation (Lewis and Ferguson 1993). The benefits from using genetically improved seedlings and fertiliser can often be reduced (Waring 1972, Flinn *et al.* 1979) and stress caused by interference can increase susceptibility to attack from pests and diseases (Nambiar 1990).

Most knowledge on weed interference in young plantations has come from empirical research with herbicides (Richardson 1993), focusing mainly on tree crop response, herbicide type, application rate, and degree of weed removal. The interfering weeds, their ecology, growth and behaviour have received less attention (Nambiar 1990, Collet *et al.* 1996a). To match appropriate weed control practices to soil, site and species requirements, greater consideration needs to be given to site quality and weed - tree interactions (Turvey 1984, Neilsen and Wilkinson 1990, Lowery *et al.* 1993, Caldwell *et al.* 1995, Richardson *et al.* 1996). The timing and duration of weed competition and the influence of resource availability are important aspects of such considerations (Richardson 1993, Wagner 1993). This information is important for determining the impact of weeds on tree growth, for understanding critical periods of

resource use and for identifying the most appropriate time to apply weed control measures (Wagner *et al.* 1996).

1.2 Background

Achieving effective weed management during plantation establishment is one of the major determinants of good early growth of the tree crop under the majority of climate, site and weed situations (Walstad and Kuch 1987, Boomsma and Hunter 1990, Richardson 1993). This is widely recognised by many industrial plantation growers in Australia and after more than 30 years of research (Boardman unpublished) has resulted in the development of successful herbicide control methods for a wide range of climate, site and weed situations. Other plantation growers however, have had less success, both in appreciating the need for effective grass control and in implementing adequate control. The poor performance of smaller-scale plantings, especially farm forestry and projects managed by community Landcare groups is not uncommon in Australia.

The dominance of herbicide-based control methods is due in large part to the success and ease of use of these chemicals in a wide variety of situations. The need to understand the weeds and their ecology has been considered less important (Nambiar 1990, Collet *et al.* 1996a). Herbicides such as glyphosate (eg. Roundup: Monsanto) are used for initial broad-spectrum 'knockdown' of weeds in many situations, however, weed 're-invasion' can occur soon after. Extended control is generally required during the establishment period, particularly during the first year of growth. Extended control is achieved by using herbicides with residual activity. Such herbicides, especially triazines and related groups, for example: hexazinone (eg.

Velpar: DuPont), atrazine (eg. Gesaprim: Nufarm) and simazine (eg. Gesatop: Nufarm) have greatly improved weed control success throughout the plantation industry in Australia. There is continuing debate on the conditions and requirement for weed control during the second year of growth (Sandover 2002), however, this is widely practiced in both pine (Adams and Dutkowski 1995) and eucalypt plantations (Fremlin and Mistic 1999).

There is increasing environmental pressure and public scrutiny of forest management and the use of herbicides, particularly relating to catchment management and water quality. There is an ongoing need, therefore, to minimise the environmental impacts of herbicides while making them more effective and efficient and appropriate to soil, site and species. The triazine group has been the major focus of attention with regards to off-site movement with implications for water quality and perceived public health.

There are various methods of improving the efficiency of herbicide use, including reducing the area treated (eg. spots or strips), improving the application and formulation technology, applying herbicides only to where weeds occur, and improving weed forecasting and timing of application. Accepting lower levels of weed control and hence tree growth rates is another way of reducing herbicide inputs. In at least one case in Australia, a major plantation grower has stopped using residual herbicides during establishment of eucalypt plantations and has been actively seeking alternative approaches and more integrated systems of management. Other growers are testing the efficacy of alternative, non-triazine, residual herbicides. Either way, it is expected that further advances in weed management, will require

greater consideration of the site quality, weed - tree interactions and the processes or mechanisms involved (Wagner 1993, Cousens 1996). The timing and duration of weed competition and the influence of resource availability are important aspects.

1.3 Competition

Much of the current research has shown that increased growth due to weed control can usually be explained in terms of improved access by the trees to water (Sands and Nambiar 1984) or nutrients (Ellis *et al.* 1985, Smethurst and Nambiar 1989, Örlander *et al.* 1996). This leads to enhancement of the trees' physiological activity (Boomsma and Hunter 1990, Richardson 1993, Mohammed *et al.* 1998) leading to increased leaf area and greater light interception by the crop (Kironko *et al.* 2002). Competition for resources is therefore considered to be the main cause of seedling growth suppression. This has been termed 'resource mediated competition' (Goldberg 1996) or 'exploitative competition' (Keddy 1989) where one plant depletes a resource which is limiting to another plant.

Other plant – plant interactions that can lead to one plant species out – performing another, include allelopathy and other direct or indirect influences. Allelopathy is where one plant releases a natural product (allelochemicals) into the environment which subsequently reduces the survival or growth of neighbouring plants (MacLaren 1983, Horsley 1988, Richardson *et al.* 1993). Many plant species including grasses are known to produce allelochemicals (MacLaren 1983, Turkington 1990). Extracts from grass have been reported to inhibit hybrid poplar growth (Spurr and Barnes 1973) and chemicals released from fescue grass inhibited loblolly pine (*Pinus taeda* L.) growth (cited in MacLaren 1983). Allelopathic

compounds can depress rates of decomposition and N-mineralisation thus affecting soil N availability (Inderjit and Del Moral 1997). Inhibition of soil processes, such as nitrification, through changes in soil microflora, have been reported by Ellis *et al.* 1985 where mycorrhizae differences occurred under *Poa* spp. compared to under *E. delegatensis* forest. This was considered to be a major reason for slow re-colonisation of grasslands by *E. delegatensis* seedlings (Ellis and Pennington 1992). Exudates from several grass species eg. rye grass (*Lolium multiflorum*) and tall fescue (*Festuca arundinacea*) were shown to inhibit root and shoot growth of seedling pampas grass (*Cortaderia selloana* (Schult) Asch. et Graeb.) (Zabkiewicz *et al.* 1998). In the same study, *P. radiata* root growth was reduced by extracts from tall fescue but not rye grass (Zabkiewicz *et al.* 1998). The concentration of allelochemicals has been reported to increase with conditions of increasing stress, eg. moisture (Ardi 1986; cited in Inderjit and Del Moral 1997), and increased nutrient availability, eg. nitrogen (Chou 1989; cited in Inderjit and Del Moral 1997).

Direct interference has been reported by Fensham and Kirkpatrick (1992) where tree seedling roots were excluded from a dense perennial grass sward due to physical resistance to root penetration. However, allelopathy was also thought to play an important role. Another example of mechanical interference is where litter from grasses such as Canada blue-joint grass (*Calamagrostis canadensis* (Michx.) Beauv), can be compressed by snow, leading to smothering and crushing of small tree seedlings in Canadian winters (Macey and Winder 2001). It has also been observed that grass with extremely sharp foliage, eg. pampas grass (*C. selloana*) has caused high levels of physical damage to *P. radiata* needles which may reduce photosynthesis (Richardson 1993).

Indirect influences include the effect of weeds on the seedling microclimate. Menzies and Chavassee (1982) reported that susceptibility of *P. radiata* seedlings to out of season frosts can be exacerbated by weeds. Weed presence can also reduce soil temperatures, reducing root growth, microbial activity and N-mineralisation (Leeper 1967, Adams and Attiwill 1986a, Whitehead 1995, Caldwell *et al.* 1995, Nilsson *et al.* 1996, Reynolds *et al.* 2000).

While direct interference may be easily demonstrated, other mechanisms involving resources or allelopathy are much more difficult to demonstrate especially under field conditions. This is especially so for allelopathy where much research has been carried out to try to demonstrate the importance of allelochemicals in plant – plant interactions and ecological processes (Horsley 1988). Due to the complexity of the processes below-ground, it is difficult to separate or decouple the factors involved, especially allelochemicals, from competition for growth limiting resources in field situations (Nambiar 1990, Turkington 1990, Richardson 1993, Goldberg 1996, Casper and Jackson 1997, Inderjit and Del Moral 1997). In a study where there was adequate water and nutrition, it was considered that a complex of interactions was responsible for the competitive mechanism between *P. radiata* seedlings and rye grass (*Lolium multiflorum*) and that no allelochemical inhibition was evident (Zabkiewicz *et al.* 1998). The characteristics of the site (and climate) and the weed and the tree crop all interact to present site-specific results. At any one site it is likely that multiple factors are involved through time and space, and the importance of any of these will change with time, during the development of trees and weeds and the environmental conditions.

The focus of this study is resource mediated plant competition and does not address interference competition occurring through other factors such as allelopathy, or resource competition between plants and soil microbes. Analysis of such competition needs to consider both the effects of plants on resources and the plant response to changes in those resources (Goldberg and Fleetwood 1987). A simplified conceptual model of resource mediated plant competition is shown in Figure 1.1. In this model plants must have an effect on the abundance of a resource and other plants must respond to the change. Both the effect and response must be of the appropriate sign for competition to occur (Casper and Jackson 1997).

While many studies can identify a resource that is limiting growth (Squire 1977, Nambiar and Zed 1980, Balneaves 1982, Knowe *et al.* 1985, Hadryanto 1994, Richardson *et al.* 1996) few can describe the processes involved, including the timing, duration, changes and interactions with other factors, during the seedling establishment period. Studies of plant competition in natural communities have been mainly phenomenological (Goldberg 1996) and concerned with species dynamics, changes in abundance and condition and successional processes (Keddy 1989). Environmental resource gradients have been used to view community changes in relation to site quality and conditions (Goldberg 1996) and commonly, information is related to growth, habit and physiological characteristics, with some value of competitive ability derived for the target species. However, these studies are not very useful for determining the actual mechanisms of plant competition (Keddy 1989, Goldberg 1996).

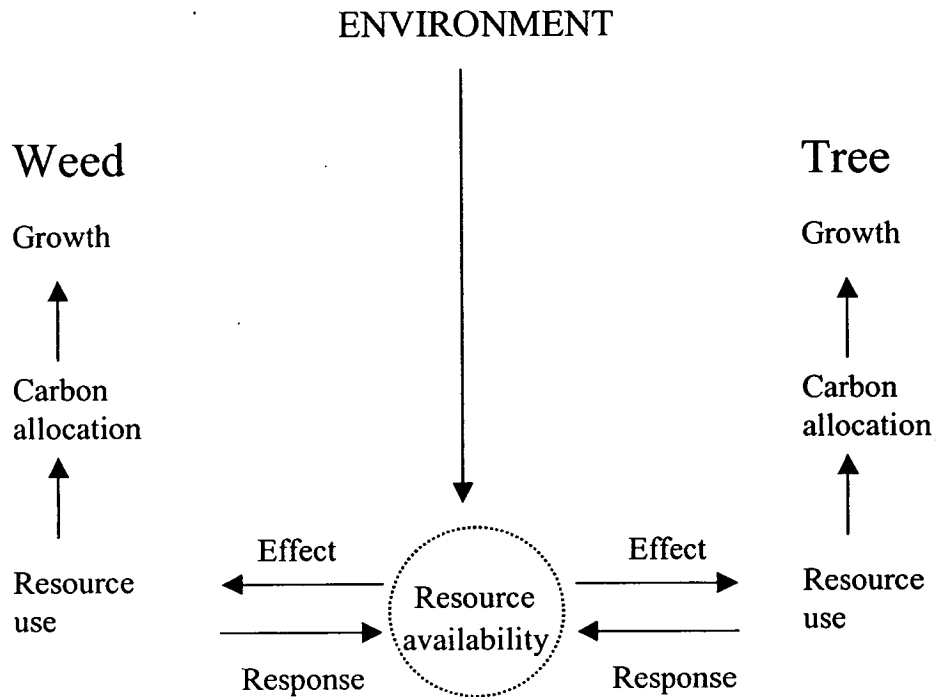


Figure 1.1 Simplified conceptual model of resource mediated plant competition (adapted from Berkowitz 1988 and Goldberg 1990).

In agricultural cropping systems, plant competition has been widely studied in terms of weed density and the effects on crop growth and development. In many cases, the weeds are similar in habit and growth to the crop. In contrast, plantation establishment on ex-agricultural sites usually deals with herbaceous weeds interacting with woody perennial tree species, and is a more difficult system to study (Tinker and Nye 2000). Silvopastoral research has studied interactions between grass and trees but mainly in relation to the effects of established trees on herbaceous plant growth. For example, the effect of *Pinus radiata*, on the productivity of pasture species has been widely studied (Hawke 1991, Kellas *et al.* 1995). Less attention has been paid to the effects of pasture on tree crops (Connor *et al.* 1987, Hadryanto 1994,

Clinton and Mead 1994a). In plantation forestry weed research is generally concerned with the establishment phase (newly planted seedlings and herbaceous weeds) where interspecific competition can be severe.

The recent large expansion of eucalypt plantation forestry in southern Australia has been onto land previously cleared for agriculture where grasses and herbaceous plants predominate. *Eucalyptus globulus* Labill and *E. nitens* (Deane and Maiden) Maiden are the tree species of main commercial interest (ABARE 1999, Burns *et al.* 1999). These plantations are managed principally for pulpwood (8 – 15 years rotation) though the proportion managed for solid wood over longer rotations is expected to increase (Pinkard and Beadle 2000). Both species have potentially rapid growth rates but their tolerance to interference by weeds during establishment is low (Neilsen and Wilkinson 1990, Schumann 1992, Fremlin and Misic 1999).

1.4 A resource-based approach

Competition is for resources; therefore the resources need to be examined to understand the mechanisms of competition (Keddy 1989, Berkowitz 1988). Soil water and nitrogen are two very important resources required for plant development and growth (Marschner 1995, Kozlowski and Pallardy 1997) and are frequently limiting growth in plantations in southern Australia (Boomsma and Hunter 1990, Weston 2001). These are often reported as the most important resources competed for, although competition for light can also be important. To examine competition between grass and young *E. globulus* during the establishment phase, a research program was carried out with funding and support from five major forest growers in southern Australia, along with CSIRO, the University of Tasmania, and the CRC for

Sustainable Production Forestry. The characteristics of soil water and nitrogen, their dynamics and interactions were examined in this study using a resource-based approach, in relation to changes in levels of availability as modified by the use of irrigation and fertiliser. The effects of *H. lanatus* and *E. globulus* on, and responses to, resource availability (Goldberg 1996) were also examined. Within this framework, critical period methodology (Neito *et al.* 1968, Zimdahl 1988) was used to determine the timing and duration of the competitive effects.

The primary weed species chosen for the study was a common perennial grass *Holcus lanatus* L. (Yorkshire fog grass), known for its vigorous growth and competitiveness. Also on site was a naturally occurring, broad-leaved herb *Acetosella vulgaris* Fourr. (sheep's sorrel). Both species were managed as the weed population at the site. *E. globulus* was the plantation species used for the study because of the national plantation dominance of this species, the greater lack of knowledge regarding this species compared to softwoods such as *P. radiata*, and the suitability of the study site for *E. globulus* growth.

1.5 Summary and major objectives

The Thesis has six research chapters (3 – 8) which progressively address the development of weeds, their impact on tree growth, and the effect on response to changing resource availability by both trees and weeds. Chapter 9 consolidates this information in the general discussion, while Chapter 10 outlines the implications for plantation weed management, based on the results and knowledge. Figure 1.2 illustrates the general structure of the Thesis.

In Chapter 3, “Growth and dynamics of *H. lanatus*”, the growth and development of the primary weed species, *H. lanatus* and the secondary broad-leaved species *A. vulgaris*, were measured during the two-year study. Germination and establishment, flowering, seed set, senescence and regrowth were examined in response to season, soil water and nitrogen treatments and *E. globulus* presence. The hypothesis was that the competitive interaction between *H. lanatus* and other plants (*A. vulgaris* and *E. globulus* seedlings) would be related to soil resource availability and season of growth. A series of critical period treatments (Zimdahl 1988, Wagner *et al.* 1996) involving removal and re-establishment of *H. lanatus* during the two-year period, were used to examine growth at different times.

In Chapter 4, “Impact of timing and duration of grass control on *E. globulus* growth”, *E. globulus* responses to weed presence and absence and to contrasting soil water and nitrogen treatments is examined, along with the timing and duration of weed competition and the influence of resource availability (Richardson 1993, Wagner 1993) on the plant interactions. The critical period method was used whereby a range of periods of weed removal and re-establishment were applied for determining the critical periods of resource-use and for determining the most appropriate time to apply weed control (Wagner *et al.* 1996). Two hypotheses were tested: (1) that the competitive effect of grass weeds on the growth of *E. globulus* would be strongest during the first year, and (2) that the timing and duration of competition would be related to the level of site resource availability and, in particular levels of available nitrogen.

Chapter 1.
Introduction

Chapter 2.
Methods
and materials



Chapter 4. *E. globulus* growth

Chapter 6. Plant water relations

Chapter 8. Plant nutrient relations

Chapter 3. *H. lanatus* growth

Chapter 5. Soil water relations

Chapter 7. Soil nutrient relations

Chapter 9.
General discussion

Chapter 10.
Conclusions

Figure 1.2 Thesis structure

Chapters 3 and 4 have been combined and published in a paper: Adams, P.R., Beadle, C.L., Smethurst, P.J. and Mendham, N.J. (2003). The impact of timing and duration of grass control on growth of a young Eucalyptus globulus Labill. plantation. New Forests, 26, 147-165.

In Chapter 5, “The soil water regime under *H. lanatus* and young *E. globulus*”, soil water content was measured and used to define the water status of the soil under the range of weed, water and nitrogen treatments during the two-year study. The hypothesis was that soil water content would be lower under grass treatments than weed-free plots, thereby indicating a strong competitive uptake by the grass, especially for the first part of the establishment period.

Chapter 6, “Influence of *H. lanatus* on the water relations of young *E. globulus*”, relates the water status of *E. globulus* to soil water status to determine the link between these factors using leaf water potential as the indicator. The hypothesis was that water stress induced by grass competition for soil water would play a major role in the weed – tree interaction at this site, especially in low irrigation treatments.

Chapter 7, “Inorganic N and P in soil solution as affected by weed control, irrigation and N-fertilisation”, examines changes in soil mineral nitrogen, using the saturated paste method (Smethurst *et al.* 1997) to determine concentrations in bulk soil solution. These concentrations were related to resource availability for weeds and trees. The hypothesis was that grass would be a strong competitor for mineral N during the first two years of plantation establishment.

In Chapter 8, “Nutritional status of *E. globulus* and *H. lanatus*”, changes in foliar nutrient status in both species is examined and related to growth responses (Chapter 3 and 4) and soil mineral N availability (Chapter 7). In this way, the importance of nitrogen competition between the weeds and trees was investigated. The hypothesis was that nitrogen would be deficient for young *E. globulus* growing in the presence of grass weeds, during the first two years of establishment. Vector analysis (Haase and Rose 1995) was used to interpret the foliar nutrient data by comparing concentration, ratio and content methods. Vector Competition Analysis (Imo and Timmer 1999) was also used to highlight non-nutritional factors involved in the weed-tree interaction.

Chapter 9, “General discussion: the competition process between *H. lanatus* and *E. globulus*”, brings all the findings together in a discussion on the timing, duration, intensity and importance of competition for soil water and nitrogen between *H. lanatus* and *E. globulus* at this site. This is followed by the main conclusions, and suggestions on future research.

Chapter 10, “Implications for management”, summarises how the findings can be used by the plantation industry for improving weed management.

2. Experimental design, establishment and management

2.1 Introduction

A large field experiment was established to address the objectives outlined in Chapter 1. The strategy was to manipulate soil water and nitrogen resources in order to simulate four site types (combinations of rainfall x fertility) and to monitor the interactions between *H. lanatus* and *E. globulus*. Irrigation and fertiliser were used to manipulate soil water and nitrogen levels, and grass presence and absence was achieved through sowing seed and the application of herbicide, as required. Under these conditions the competitive interaction between the “weed” (*H. lanatus*) and young *E. globulus* was studied. This chapter outlines the design, establishment and maintenance of experiments at the field site.

2.2 Site description

2.2.1 Location

A 2.2 ha plantation was established in 1996 on an ex-pasture site near Penna, approximately 15 km northeast of Hobart, Australia (42° 48' S, 147° 28' E, Figure 2.1).

2.2.2 Landscape

The natural landscape of the area is dominated by Mt Lord (278 m asl) with its steep hills and ridgeline to the east of the experiment site. Steep slopes run down from the ridge top onto lower foot slopes then fan out onto flats and rolling dunes, finally

ending at low cliffs (6 – 10 m) above Pitt Water estuary (Figure 2.1). Rolling dunes created by wind-blown sand constitute the landform of the experimental site with gentle slopes of 3 – 4.5 degrees (5 – 8%). The experiment is approximately 6 m asl with the central section lower than either end. The difference in height from the lowest point to the highest point at the western end is 1.5 m.

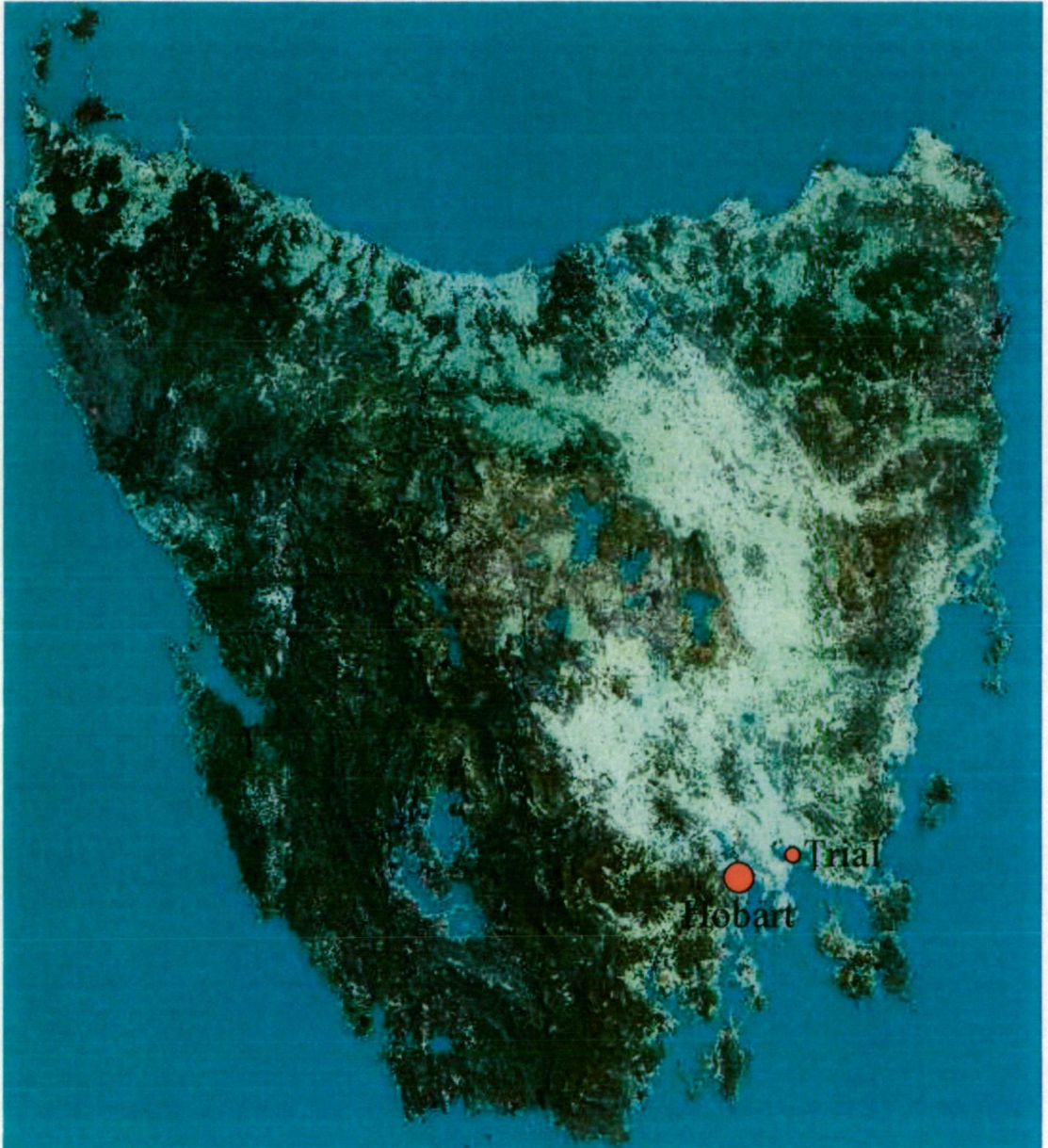


Figure 2.1 Tasmania and location of experiment site
(Source: GIS section, Forestry Tasmania)

2.2.3 Site history

The site originally supported woodland vegetation including scattered large *Eucalyptus viminalis* (Manna gum) and *Allocasuarina verticillata* (Drooping She Oak) with an understorey of *Banksia marginata* (Honeysuckle) and *Bursaria spinosa* (Blackthorn). *Pteridium esculentum* (bracken fern) and tussock grasses (*Poa* spp) were the ground cover. This vegetation was replaced by the introduction of cropping (mainly cereals) and grazing by cattle and sheep from the 1920s.

A land capability assessment (Noble 1992), done as part of the property management plan, has classified the rolling dunes as Capability Class 6e, with limitations cited as wind erosion and low nutrient levels. Current land uses include grazing and some limited irrigation of crops. At the time of plantation establishment, the site supported a one-year-old *Medicago sativa* (lucerne) crop. It was managed as a dryland crop but did receive some irrigation (via travelling irrigator) and fertiliser (super phosphate) to assist establishment and occasionally afterwards. Lucerne growth, however, was not uniformly successful and productivity was low due to the short stature of the *M. sativa* plants, their scattered and patchy nature, and the dominance of an *A. vulgaris* understorey. *Pinus radiata* planted in 1989 and 1992 adjoins the site on the western and southern sides (Figure 2.2).

2.2.4 Climate

The local climate is temperate, dry and cool. Average weekly maximum and minimum temperatures measured at the closest weather station (Hobart airport 5 km from the site) were 17.3°C and 7.9°C respectively. Occasional ground frosts occurred. There was an average of 26 days per year when the minimum temperature was 2°C or lower. Mean annual rainfall is 512 mm uniformly distributed throughout

the year (Figure 2.3). Mean annual pan evaporation is 1307 mm (2.5 times greater than rainfall), being highest in January ($192 \text{ mm month}^{-1}$) and lowest in June (38 mm month^{-1}).

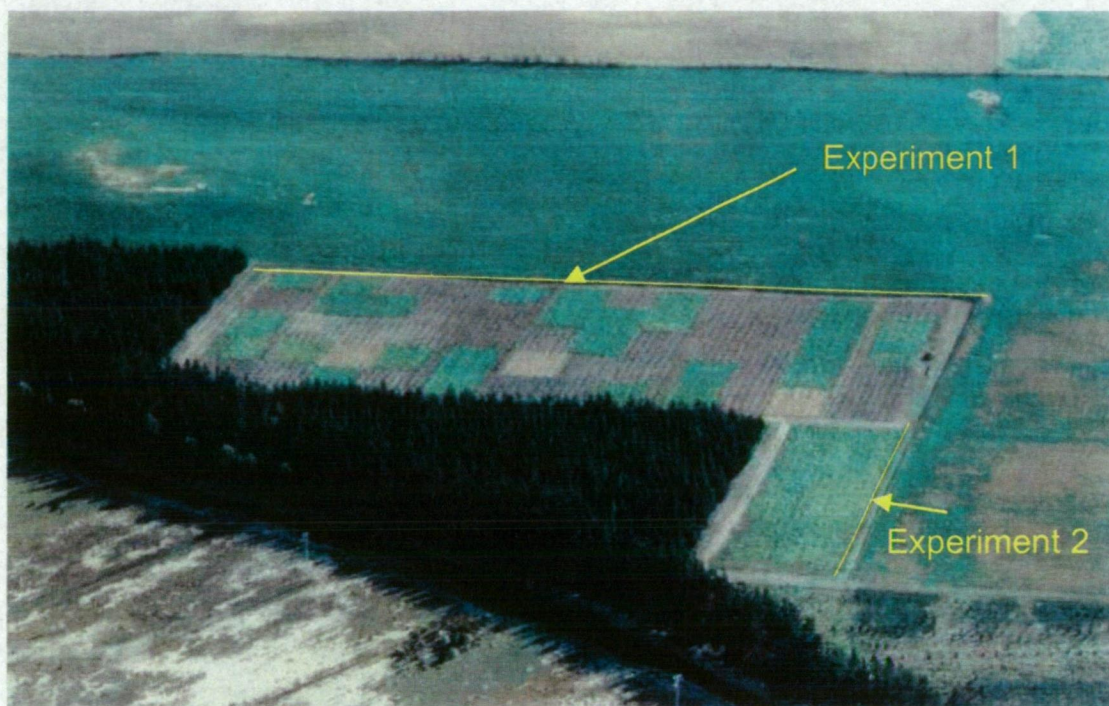


Figure 2.2 The Penna experimental site. In experiment 1 green squares indicate weedy plots, bare plots with tree rows evident, indicate weed-free plots, and straw coloured squares indicate recently controlled weed plots. Experiment 2 involves all weedy plots (Photo: M. Piesse, Forestry Tasmania June 1997).

The northern boundary of the experiment was directly exposed to the prevailing NW wind (down the Coal River valley). This wind is strongest during autumn and spring. Most of the site was sheltered by the *P. radiata* from the afternoon SE sea breeze.

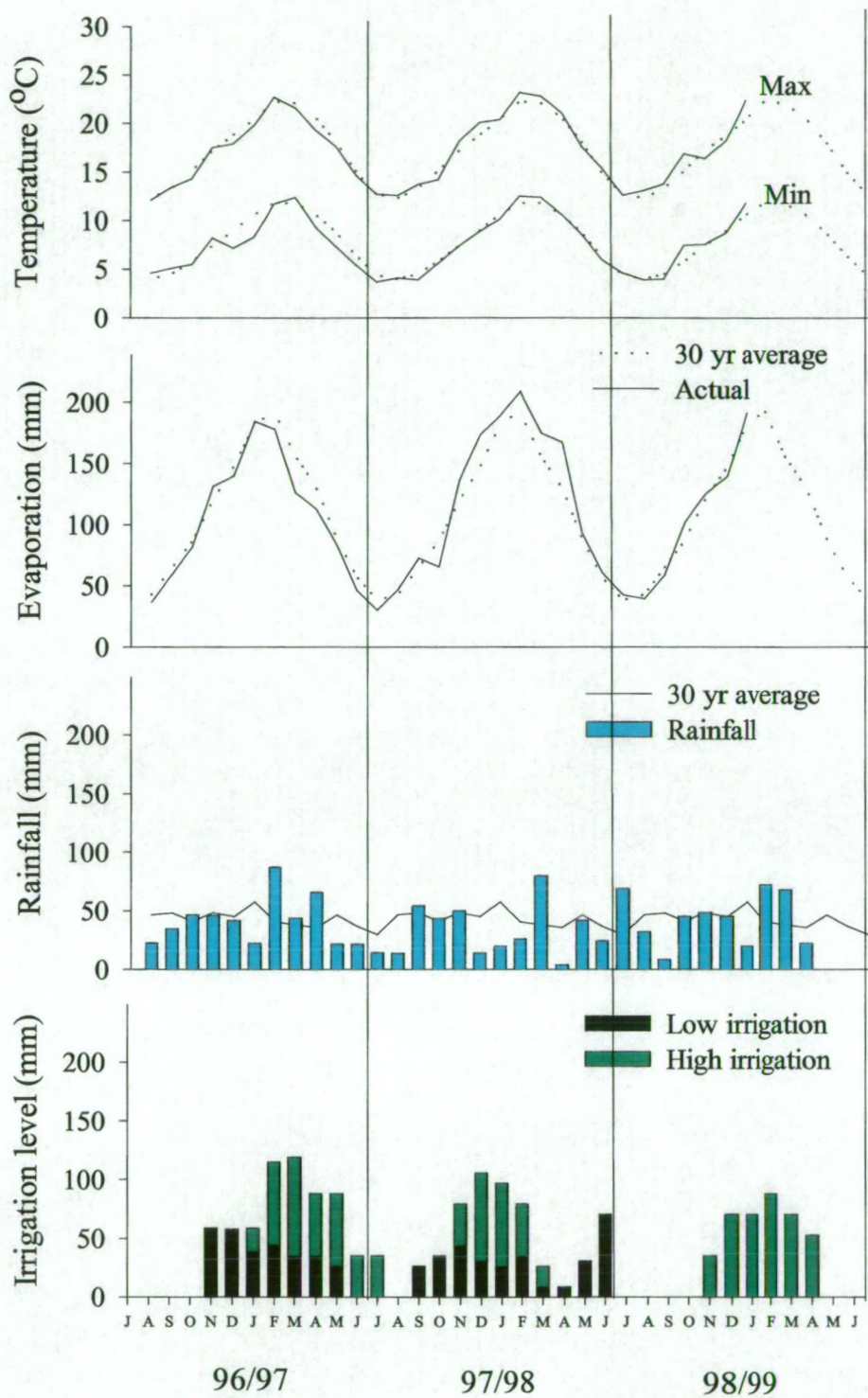


Figure 2.3 Temperature, evaporation, rainfall and irrigation at the site.

For the period July 1996 to December 1998, monthly temperature and evaporation closely followed the long-term meteorological average in both distribution and magnitude. Rainfall distribution and magnitude was more variable. In the second half of 1996, average rainfall was 27% lower and early spring was dry. Rainfall in 1997 was 12% less than average (449 mm) and both winter and early summer were dry (Figure 2.3). Rainfall in 1998 was average but there were dry periods in autumn and spring. Rainfall during summer was mainly infrequent large events.

2.2.5 Soil

The soil is duplex (Podosol, Isbell 1996) with an aeolian derived sandy A horizon overlying a sandy clay to clay B horizon at 1.3 to 2.0 m depth (Figure 2.4).

Suitability for plantations was regarded as moderate to marginal. The clay B horizon was imperfectly drained and a seasonal water table was present.

2.3 Site preparation and plantation establishment

The initial site vegetation (*M. sativa* and *A. vulgaris*) was treated using MCPA (MCPA 500: Nufarm; rate 0.3 kg ha⁻¹ a.i.) followed by a light cultivation across the site (5–7 cm depth) with a spring tyne harrow. *H. lanatus* seed was drilled in late winter (August 1996) in rows approximately 10 cm apart and 1 cm deep at a rate of 5 – 6 kg ha⁻¹. Superphosphate fertiliser was drilled below the seed at the same time supplying 12 kg P ha⁻¹. The drilling operation also provided extra cultivation of the surface soil. *A. vulgaris* readily re-established from plant fragments and seed after cultivation.



Figure 2.4 Soil profile at Penna experimental site

Two months later (October 1996) when the site irrigation system was operational, containerised seedlings of *E. globulus* (Jerralang provenance from southeast Victoria) grown in Hiko™ trays (V-93 trays, Hiko GmbH and Co. KG, Dittersdorf, Germany) were hand planted at 2.5 m square spacings (1600 stems ha⁻¹) using spades. Rows were aligned north-south and east-west. The seedlings were planted deep (ground surface 3 – 4 cm above root collar) to reduce the impact of possible unfavourable weather soon after planting by providing access to moist soil and to allow for settling of the cultivated sand. At this time seedlings were approximately 10 months old with heights ranging from 15 – 30 cm. These were graded into three height classes and then planted into the three experimental blocks (see below) with the tallest in Block 1 and the shortest in Block 3. Several hundred surplus seedlings

were kept as refills during the first 12 months. Planting took two days employing five planters and was done by block according to seedling size.

2.4 Experimental design and treatments

Two main experiments were used to achieve the objectives outlined in Chapter 1. Experiment 1 had contrasting levels of water and nitrogen with a subset of treatments used for the critical period method. Experiment 2 involved a range of N-fertiliser rates applied in the presence of weeds receiving high irrigation. Details are given below.

2.4.1 Experiment 1. Contrasting water and nitrogen

Irrigation, nitrogen and weed treatments were arranged in a split-plot design with three replicates. Two levels of irrigation, I_{Low} and I_{High} were applied to simulate two ‘rainfall’ levels (rainfall plus irrigation) of 800 mm and 1200 mm yr⁻¹, respectively. Within these irrigation treatments, two levels of nitrogen, N_{Zero} and N_{High} were applied to provide low and high nitrogen fertility. Within each of these treatment combinations, 24-month weedy (W) or weed-free (WF) treatments were imposed (Table 2.1) (Figure 2.5). In a subset of plots receiving I_{Low} , a range of weedy and weed-free periods were applied (Table 2.2). Periods of six (in N_{High}) or 12 (in N_{Zero}) months were chosen to accommodate the potentially high rates of tree growth, the patterns of grass growth and seasonal effects.

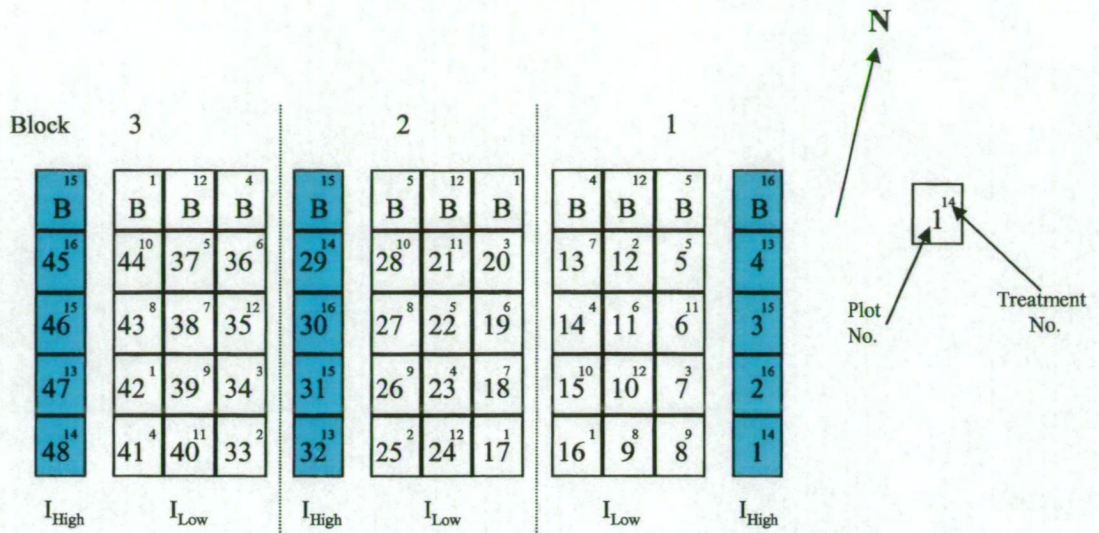
Plots were 15 m wide x 17.5 m long and contained 56 tree seedlings (7 rows by 8 trees). This included a common buffer row along plot boundaries. The internal measurement plot contained 12 trees (3 rows by 4 trees), with adjacent measurement

Table 2.1 Treatments in Experiment 1 (Set 1). Two irrigation levels, two nitrogen levels, and 0 – 24 months weed presence (W) or absence (WF).

Irrigation	Nitrogen	Weeds
I _{Low}	N _{Zero}	W 24
		WF 24
	N _{High}	W 24
		WF 24
I _{High}	N _{Zero}	W 24
		WF 24
	N _{High}	W 24
		WF 24

Table 2.2 Critical period treatments in Experiment 1 (Set 2). One irrigation level, two nitrogen levels, and 0 to 24 months weed presence (W) or absence (WF) in 6 or 12 monthly intervals. Only treatments within N_{High} were used for determination of critical period curves.

Irrigation	Nitrogen	Weeds
I _{Low}	N _{Zero}	W 12
		W 24
		WF 12
		WF 24
	N _{High}	W 6
		W 12
		W 18
		W 24
		WF 6
		WF 12
		WF 18
		WF 24



Treatment	Irrigation	Nitrogen	Weeds
1	I _{Low}	N _{Zero}	W 24
2			WF 12
3			W 12
4			WF 24
5		N _{High}	W 24
6			WF 6
7			WF 12
8			WF 18
9			W 6
10			W 12
11			W 18
12			WF 24
13	I _{High}	N _{Zero}	W 24
14		N _{High}	WF 24
15			W 24
16			WF 24

Figure 2.5 Experiment 1 layout and treatment codes

plots separated by three buffer rows. The stocking rate ($1600 \text{ stems ha}^{-1}$), higher than current industry practice ($1000 - 1400 \text{ stems ha}^{-1}$), was a compromise between having espacement wide enough to slow the onset of intraspecific competition and close enough to enable the experiment to fit into the available land area.

Irrigation

The I_{High} treatment was scheduled to maintain high water availability for the seedlings and weeds while in the I_{Low} treatment, water levels were anticipated to be limiting but adequate to maintain seedling survival. Each replicate was divided into zones of approximately equal size (0.144 ha) and water was applied to all plots within each zone according to the designated level (Figure 2.5). The water was delivered by flow compensated micro-sprinklers (DAN 2001, Kibbutz Dan, Israel) every 5 m on 30 cm high spikes. Sprinklers were placed in every second row and offset by 2.5 m to provide total ground coverage. The sprinklers were pressure compensating and at pressures $>200 \text{ kPa}$ delivered 55 litres h^{-1} (approximately 4.4 mm h^{-1}) (Figure 2.6a,b,c).

Irrigation was applied weekly in 8 - 12 mm applications between 1800 and 0700 h, unless there had been a major rainfall event in the previous week. Over the summer months I_{High} was increased to 20-30 mm per week. Each winter, all irrigation was stopped, except during the first winter, when little rain fell. When the trees had reached two years of age, I_{Low} treatments received rainfall only.



Figure 2.6 Irrigation system. (a) Water channel, intake valve, and pump, filter, flow meter and fuse box housing controllers. (b) Dan 2001 micro-sprinkler and 19 mm lateral (c) Station 11, I_{Low} , *E. globulus* age two months. Foreground shows 50 mm mainline, with 25 mm head pipe for the station zone, with 19 mm laterals along tree rows.

Table 2.3 Total fertiliser application to site (Experiment 1)

Year	Month	Product	Rate kg ha ⁻¹	Application method	Elements applied							
					N kg ha ⁻¹	P kg ha ⁻¹	K kg ha ⁻¹	S kg ha ⁻¹	Ca kg ha ⁻¹	Mg kg ha ⁻¹	Cu kg ha ⁻¹	Zn kg ha ⁻¹
1995		Superphosphate	100	Total T	0	8	0	11	20	0	0.00	0.00
1996	Aug	Superphosphate	150	Total drill	0	12	0	17	30	0	0.00	0.00
	Dec	PK blend	714	Total T	0	57	79	79	143	0	0.00	0.00
		Super + Trace elements	290	Spot H	0	23	0	32	58	0	1.65	2.00
1997	Apr	Urea	325	Total H + slit H	150	0	0	0	0	0	0.00	0.00
	Oct	Urea	652	Total H	300	0	0	0	0	0	0.00	0.00
1998	Apr	Urea	652	Total H	300	0	0	0	0	0	0.00	0.00
	June	Zincsol	5.9	Foliar spray	0	0	0	0	0	0	0.00	0.00
		Coppersol	16.4	Foliar spray	0	0	0	0.56	0	0	1.10	0.00
		Super + Trace elements	460	Total H	0	51	51	45	36	16	2.21	2.12
	Oct	Urea	325	Total H	150	0	0	0	0	0	0.00	0.00
Total			3690.3		899	151	129	183	287	16	4.96	4.12

Notes: Rate = product application rate kg ha⁻¹

Application method: Total T = Broadcast application via tractor spreader; Total H = broadcast application via hand shakers

Spot = spot applied to soil surface next to seedling; Slit H = fertiliser applied to spade slit then covered over.

Foliar spray = total application via motorised mister mounted on hand pulled trolley

Nutrition

The high nitrogen (N_{High}) treatment involved two applications per year (autumn and spring) of urea fertiliser, providing a total of 900 kg N ha^{-1} (150, 300, 300 and 150 kg N ha^{-1}) over the two years. The nil (N_{Zero}) treatment received no urea fertiliser. Other nutrients were applied (broadcast and spot) to both treatments at the same time as urea providing a total of P (151 kg P ha^{-1}), K (129 kg K ha^{-1}), Mg (16 kg Mg ha^{-1}). Foliar applications of copper and zinc were applied across the site in autumn 1999 ($4.8 \text{ kg Cu ha}^{-1}$ and $5.1 \text{ kg Zn ha}^{-1}$, respectively) to ameliorate possible deficiency symptoms of these nutrients (Table 2.3).

Weed control and re-establishment

Weed-free (WF) treatments were achieved by applying herbicides. Glyphosate ($1.5 \text{ kg ha}^{-1} \text{ a.i.}$) was used for broad-spectrum control, while haloxyfop (Verdict: DowElanco; rate $0.2 \text{ kg ha}^{-1} \text{ a.i.}$) for selective grass control and clopyralid (Lontrel: DowElanco; rate $1.0 \text{ kg ha}^{-1} \text{ a.i.}$) for control of remnant *M. sativa* and other broadleaved weeds were also used. Close monitoring and application of glyphosate enabled successful maintenance of weed-free conditions in appropriate treatments and for desired periods. Where re-establishment of *H. lanatus* was required after an initial weed-free period (treatments WF6, WF12 and WF18) seed was drilled with a single-row seeder between tree rows followed by hand broadcasting. In the W treatments (W6, W12, W18), glyphosate was used to control plants at the end of each period of presence. *A. vulgaris* was allowed to naturally re-seed and form part of the weed population.

2.4.2 Experiment 2. Soil nitrogen availability

Under the high irrigation treatment (I_{High}) and in the presence of weeds, a range of nitrogen rates were applied as urea fertiliser, to plots and the concentration of soil solution nitrate and ammonium monitored. This study commenced when the trees were 12 months old. The objective was to (a) determine the relationship between growth of *E. globulus* and the concentrations of ammonium and nitrate in soil solution (0-10 cm depth) in a weedy plantation growing on sand with adequate water and other nutrients.

Design and Treatments and application

A randomised block design with two replications was used (Figure 2.7). Five levels of nitrogen were applied as urea fertiliser at various rates (Table 2.4). Urea was applied via hand shakers and carry bags. Two replications for this experiment is clearly lower than that desired for this type of study. However, the size of the experiment was constrained by available space at the site.

Table 2.4 Experiment 2. Five levels of nitrogen application. For the purposes of this study only Oct 1997 and Mar 1998 have been used in the analysis (reflected in the treatment code). All plots had one irrigation level (I_{High}) and one weed treatment (W).

Treat No.	Treatment	Nitrogen applied (kg N ha ⁻¹)		
		Oct 1997	Mar 1998	Oct 1998
1	N ₀	0	0	0
2	N ₂₀₀	100	100	50
3	N ₄₀₀	200	200	100
4	N ₈₀₀	400	400	200
5	N ₁₂₀₀	600	600	300

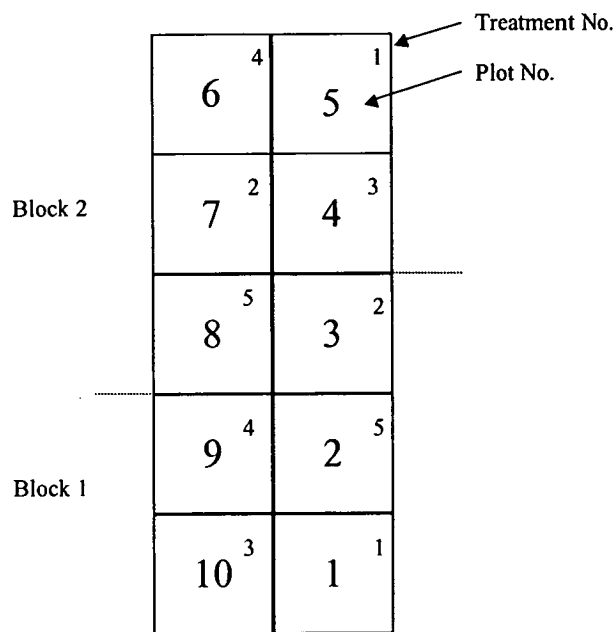


Figure 2.7 Experiment 2 layout

2.6 Methods and measurements

Plant growth (weeds and trees), soil and plant water relations, soil and plant nutrient relations and site and climate measurements were made during the two-year study. A detailed account of the methods and materials is provided in appropriate chapters.

2.7 Symbols, abbreviations and units

A summary of symbols, abbreviations and units used in the thesis are given in Table 2.5.

Table 2.5 Summary of symbols, units and abbreviations

Symbol	Description	Units
<i>Treatments</i>		
W, WF	Abbreviations for Weedy and Weed-Free	—
I _{Low} , I _{High}	Abbreviations for Low and High Irrigation	mm
N _{Zero} , N _{High}	Abbreviations for Low and High Nitrogen	mm
N ₀ – N ₁₂₀₀	Abbreviations for Nitrogen rate experiment	kg N ha ⁻¹
<i>Climate parameters</i>		
T	Air temperature	°C
R	Rainfall	mm
AEST	Australian Eastern Standard Time	
h	hour	
<i>Soil parameters</i>		
θ_s	Soil water content	mm
θ	Volumetric soil water content	mm
Δ_w	Soil water deficit	mm
K _d	Solid – liquid partition coefficient	
W	Total water content	mm
W _{max}	Maximum water content	mm
W _a	Plant available water	mm
W _f	Field capacity	mm
W _o	Permanent wilting point	mm
P _b	Bulk density	g cm ⁻³
A, B	Modified Freundlich equation parameters	
LOI	Loss on ignition	%
EC	Electrical conductivity	dS m ⁻¹
NNM	Net nitrogen mineralisation	kg N ha ⁻¹ y ⁻¹
<i>Plant parameters</i>		
ht	Tree height	m
D ₁₅	Tree diameter at 0.15 m (above-ground)	cm
DBH	Tree diameter at breast height (1.3 m)	cm
D _{inc}	Diameter increment	cm
V	Tree volume	cm ³
H/D	Height : diameter ratio	
RGR	Relative growth rate	
L*	Leaf area index	Dimensionless
W _d	Leaf dry weight	g
E _t	Evapotranspiration	mm
E _p	Pan evaporation	mm
ψ_L	Leaf water potential	MPa

Table 2.5 continued:*Plant parameters* (continued)

Ψ_{\max}	Pre-dawn leaf water potential	MPa
Ψ_{\min}	Midday leaf water potential	MPa
A_{\max}	Maximum photosynthetic rate	$\mu\text{mol m}^{-2} \text{s}^{-1}$
g_s	Stomatal conductance	$\text{mmol m}^{-2} \text{s}^{-1}$
L_v	Root length density	cm cm^{-3}
k	Crop factor	E_t / E_p
YFE	Youngest fully expanded leaves	

Other

asl	Above sea level	m
TEI	Time of equal interference	
EIF	Effluent irrigated plantations	
CRR	Count rate ratio	
NMM	Neutron moisture meter	

3. Growth and dynamics of *H. lanatus*

3.1 Introduction

This chapter examines the growth and dynamics of a perennial grass: *Holcus lanatus* L. (Yorkshire fog grass) and a rhizomatous broadleaf: *Acetosella vulgaris* Fourr. (Sheep's Sorrel) under contrasting levels of soil water and nitrogen availability in a young *E. globulus* plantation.

H. lanatus is a temperate, perennial grass, native of Europe, the Mediterranean and East Asia which has become naturalised in many cool temperate regions including south-eastern Australia (Lamp and Collet 1976). It is a loosely or densely tufted erect perennial between 20 – 100 cm in height (Figure 3.1), which is early maturing and has vigorous growth on wet and acid soils, and is considered to be indicative of poorly drained soils. However it is adaptable to a wide range of growing conditions (Langer and Hill 1991). It is a very common invader of poor pasture, roadsides and waste areas (Curtis and Morris 1994) and also sown pastures where it competes with the better, more palatable grasses (Lamp and Collet 1976). Where the species is persistent, it is considered to be competitive (Silvertown *et al.* 1992). Its rapid growth under favourable soil nutrient and water conditions enables it to develop into a dense vigorous sward which can shade out other less vigorous species and low growing broad-leaved plants, such as *Trifolium repens* (White clover) (Turkington, 1990) or *A. vulgaris* (Nielsen, 1998). In a study of 24 wild plants with a C₃ type photosynthesis, Poorter *et al.* (1990) reported that *H. lanatus* had a high leaf area ratio (leaf area : total plant dry weight ratio) and a high relative growth rate (RGR).

These characteristics encouraged the use of *H. lanatus* as a major component in covercrop seed mixtures during plantation establishment in New Zealand (West and Dean 1992).



Figure 3.1 *Holcus lanatus*, a flowering plant
(Illustration: D. Morris, Tasmanian Herbarium).

A. vulgaris is a broadleaf plant native of Europe and is now widespread in cultivated ground, waste places and pastures throughout southern Australia. Mature plants have a prostrate, spreading habit and erect flowering stems. The leaves can be 4 – 20 cm long and form a loose, untidy rosette (Hyde-Wyatt and Morris 1975) (Figure 3.2). It has a proliferating slender root system (rhizome), capable of extensive and rapid spread by vegetative means, especially if disturbed or broken up through cultivation (Smith 1975). It can be strongly competitive and smother other vegetation, but it is susceptible to competition from strongly growing crops and good pasture (Hyde-Wyatt and Morris 1975) that provide direct competition for light, water and nutrients (Smith 1975). Where vigorous pasture can be maintained, *A. vulgaris* will only be present at low levels. It does however have a wider tolerance of stress factors than other co-species, and grows well and persistently under conditions of low fertility and acid soils (Harris 1971). Where grass is removed by herbicides in young plantations, *A. vulgaris* can often proliferate, and because it can maintain succulent vegetation longer than many grasses during summer, it can cause severe water stress to young tree seedlings (Nambiar and Zed 1980).

Both weeds are representative of herbaceous species commonly found in plantations throughout temperate Australia and both are known to cause strong negative effects on the growth of young trees (Nambiar and Zed 1980, Boomsma and Hunter 1990, Richardson 1993). The hypothesis to be tested was that the competitive interaction between *H. lanatus* and other plants (*A. vulgaris* and *E. globulus* seedlings) would be related to soil resource availability and season of growth. To test this, irrigation and nitrogen application was used to simulate four site types, and a range of periods of weed introduction and weed removal (presence and absence) were applied (critical

period treatments, Zimdahl 1988). This enabled evaluation of grass growth and development during the two-year study and also the effect of duration and timing of weed presence and absence on tree growth (Chapter 4 *E. globulus* growth).

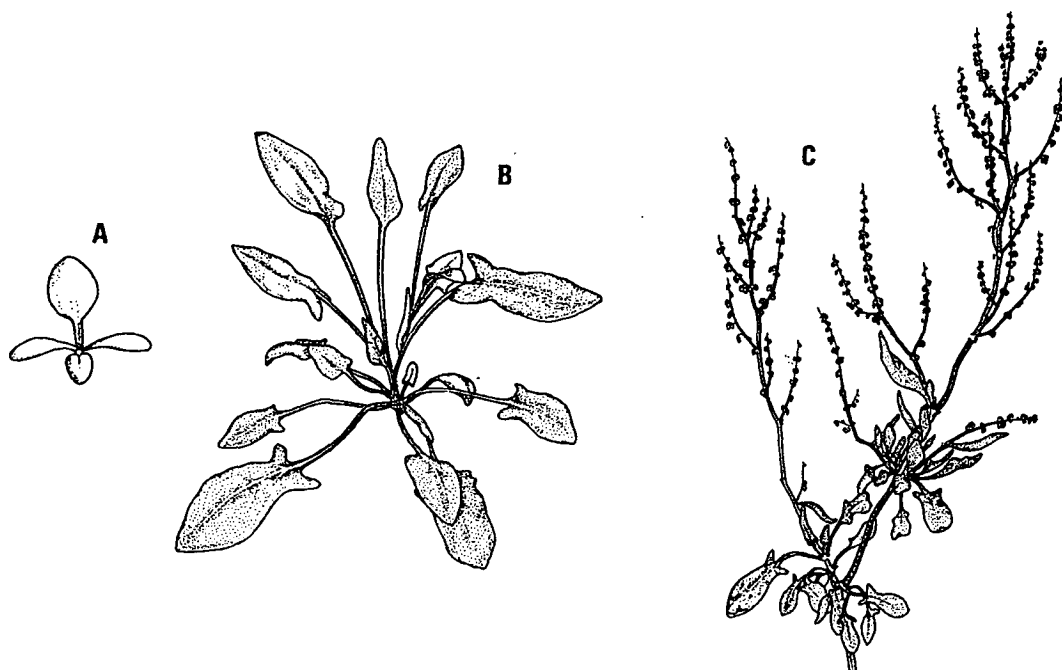


Figure 3.2 *Acetosella vulgaris* (a) seedling (b) young plant (c) flowering branch
(Illustration: D. Morris, Tasmanian Herbarium)

The objectives were:

1. To examine how *H. lanatus* and *A. vulgaris* interact under contrasting levels of soil moisture and nutrient availability during the first two years of *E. globulus* plantation establishment.
2. To examine the effect of timing and duration of a range of weed removal and introduction periods on subsequent weed development and growth.
3. To determine what this means for resource demand, resource use and potential for competition to occur.

3.2 Materials and methods

3.2.1 Treatments

Both levels of irrigation (I_{Low} and I_{High}) and nitrogen (N_{Zero} and N_{High}) were used to determine how *H. lanatus* and *A. vulgaris* interacted under contrasting levels of soil moisture and nutrient availability during the first two years of *E. globulus* plantation growth. Critical period treatments were used to examine the effect of timing and duration of a range of weed removal and introduction periods on subsequent weed development and growth. Further experimental details are provided in Chapter 2.

3.2.2 Measurements

Assessment of *H. lanatus* and *A. vulgaris* per cent groundcover was carried out seven times during the first two years, using five 1 m² quadrats plot⁻¹. Each 1m² quadrat was divided into 10 x 10 cm squares to aid visual assessment. The weed community, particularly *H. lanatus* was very uniform across the site, therefore quadrats were located systematically within plots. The mean per cent ground cover for each plot was calculated from five assessments per plot. All plant foliage (live and dead) was included. For most dates the bulk of the foliage was live and green. However, there were some yellow and dying leaves at the shaded base of plants and this was not separated from live herbage during assessment. It was not until the second summer (1997/98), approximately 16 months after sowing, that most of the grass tops had died back leaving very little live herbage. A full per cent cover assessment was not made at this time. By autumn 1998, new foliage had started to appear at the base of grass plants and regrowth was well advanced. At this time, both live (green) and dead (brown) leaf per cent cover was assessed.

Above-ground weed biomass (dry mass t ha⁻¹) was harvested on three occasions using four randomly located 0.25 m² quadrats in each plot. At age 10 and 15 months all above-ground biomass was assessed as live. At age 19 months, in the second autumn after sowing, the dead biomass component, was separated and measured. The weeds were cut at ground-level with a sharp knife, harvested, bagged, labelled and transported back to the laboratory where each sample was separated into three classes - *H. lanatus*, *A. vulgaris* and Other. These sub samples were separately re-bagged, air dried for several days to remove most of the moisture, and then oven dried for 24 h at 70°C. Samples were then weighed and recorded. Replicate samples from each plot were bulked and sub samples were collected for nutrient analysis.

3.2.3 Data analysis

Mean plot per cent ground cover of each weed species (including bare ground) and the total population groundcover were calculated and analysed by ANOVA (Genstat 5 Committee 1994) as a factorial design. Three plots were excluded due to grass mortality on the final two assessment dates and were analysed as 'missing data'. *H. lanatus* biomass data were analysed as above. Differences between treatments were considered significant when the p value was < 0.05.

3.3 Results

H. lanatus was the dominant weed (Figure 3.3a). Results refer only to main effects because interactions were non-significant ($p > 0.05$). Mean per cent ground cover was 83% (± 6) (mean ± 1 SE) in all weed treatments eight months after sowing, after which treatment differences became evident. This cover was maintained over the following winter and spring until flowering, seed set and senescence in the second

summer (17 months after sowing). Regrowth occurred in the second autumn.

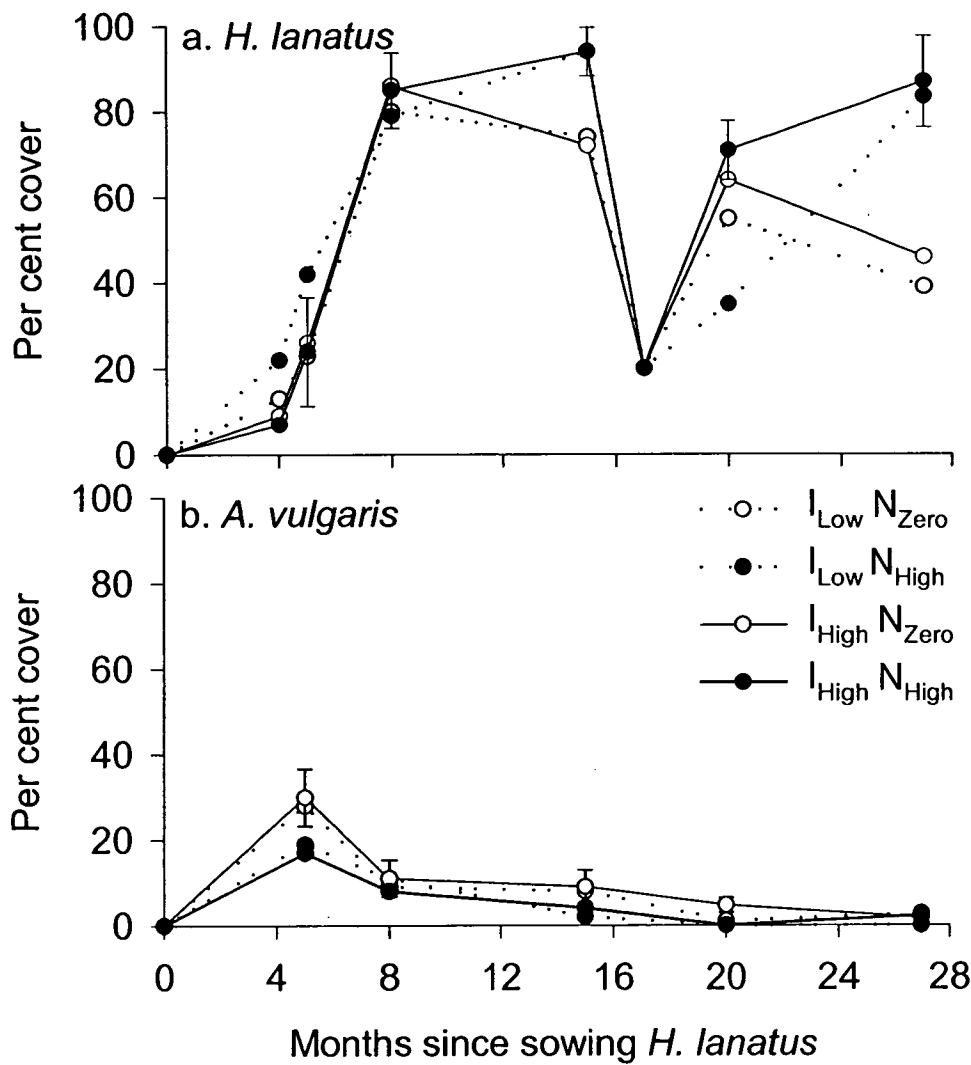


Figure 3.3 (a) *H. lanatus* per cent ground cover (b) *A. vulgaris* per cent ground cover. Error bars indicate LSD's ($p=0.05$).

The main response at both levels of irrigation was to N_{High} in the second spring (15 months after sowing) when there was a 22% increase in cover over N_{Zero} ($p<0.05$). Flowering and seed set in N_{High} preceded that in N_{Zero} by three to four weeks (Figure 3.4a). Regrowth at I_{Low} was slower in N_{High} compared to N_{Zero} while it was faster in

I_{High} compared to I_{Low} . By the third spring (26 months after sowing), weed cover was again significantly higher ($p < 0.05$) in N_{High} than N_{Zero} treatments (76% and 42%, respectively). At this time, dead grass was significantly greater ($p < 0.05$) in N_{Zero} than N_{High} treatments (42% and 13% cover, respectively), as was bare ground (10 % and 1% cover, respectively). Grass health and condition in unfertilised, low irrigation treatments declined during the two-year study, exhibiting leaf chlorosis and small leaves. It appeared that native soil N resources were limiting the growth of *H. lanatus*. This was particularly apparent in Block 3.

Per cent cover of *A. vulgaris* initially was similar to that of *H. lanatus*, but decreased with increasing dominance of *H. lanatus* (Figure 3.3b). It was most persistent in Block 3 (Figure 3.4b).

Biomass production of *H. lanatus* (Table 3.1) followed the trends in seasonal ground cover. In the first winter (10 months after sowing) *H. lanatus* constituted up to 95% of the live weed dry mass and was increased by N_{High} (62%) ($p < 0.10$). Live dry mass increased in the second spring (15 months after sowing) with a large response to N_{High} (up to 14 t dry mass ha^{-1}) which was significant ($p < 0.05$) in I_{Low} . In the second autumn (19 months after sowing) total dry mass (live and dead) ranged from 9 - 12 t ha^{-1} . There were no significant differences between treatments in either live or dead dry mass. There was greater dry mass in the dead component, while live dry mass was only 1.4 – 2.2 t ha^{-1} . Biomass production of *A. vulgaris* was variable across the site with no significant treatment effects (data not shown), though it was greatest in Block 3 where the grass sward was poorer.

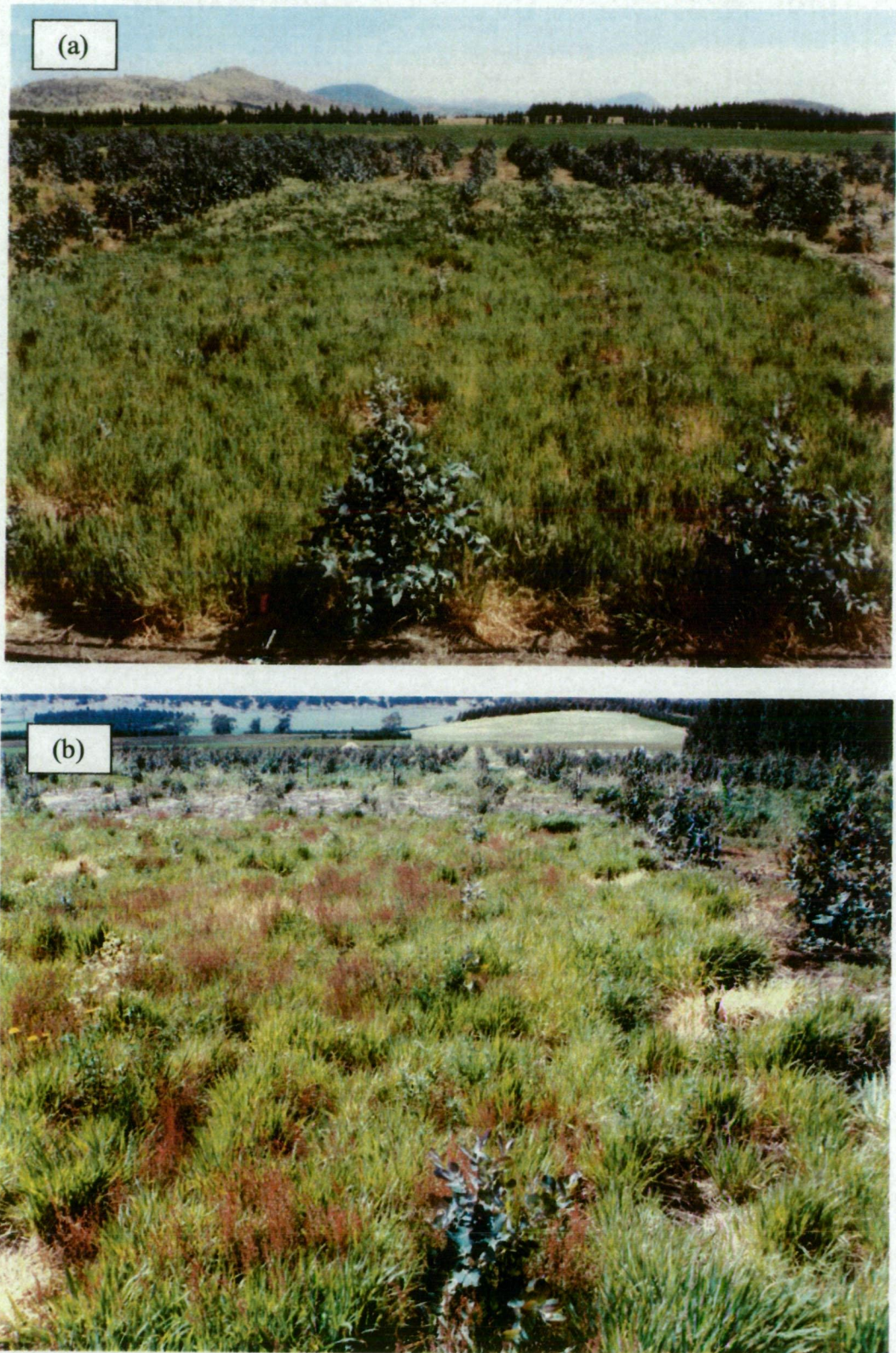


Figure 3.4 (a) vigorous *H. lanatus* growth in spring (November 1997) in Block 2. High irrigation, weedy zone in foreground, with weed-free zone in background. Front half of weedy zone is N_{Zero} , back half is N_{High} , with earlier flowering evident (b) *H. lanatus* and *A. vulgaris* (red flower) (low irrigation and unfertilised) in Block 3 (November 1997).

Table 3.1 Biomass production of *H. lanatus*, 10 (winter), 15 (spring) and 19 (autumn) months after sowing. Within each date, treatments appended by the same letter are not significantly different ($p<0.05$).

Treatment	<i>H. lanatus</i> biomass production (dry mass (t ha ⁻¹))							
	10 months		15 months		19 months			
	Live		Live		Live		Dead	
I _{Low} N _{Zero}	6.004	ab	9.514	a	1.453	a	8.953	a
I _{Low} N _{High}	9.381	b	13.997	b	1.840	a	10.409	a
I _{High} N _{Zero}	5.765	a	11.199	ab	2.197	a	9.992	a
I _{High} N _{High}	9.145	ab	13.755	b	1.338	a	10.662	a

Treatments (W) that required weed removal (Figure 3.5a) were more successful (implementation and results) than those that required re-establishment of weeds (WF) (Figure 3.5b). At the six-month weed removal, *H. lanatus* cover was 92 % (\pm 8). The grass died completely within two to three weeks of herbicide application. Standing dead herbage and surface litter remained for up to 12 months before flattening down, and longer before bare soil started to appear. Grass cover at the 12-month weed removal was also high at 81% (\pm 19) before herbicide application (Figure 3.5a). At the 18-month weed removal, the grass had flowered, set seed and ‘hayed off’, leaving 10 – 15% live cover before herbicide was applied (Figure 3.5a).

Germination and sward development in weed re-establishment treatments (WF) was slow. In the six-month treatment, cover was 54% (\pm 9) and 60% (\pm 19), respectively, six and 12 months after sowing (Figure 3.5b). Re-establishment in the 12 month treatment was unsuccessful, as it was attempted in early summer when soil temperature and rapidly increasing soil moisture deficits were detrimental to germinating grass plants. In the 18-month treatment, cover was 54% (\pm 12) six months after sowing.

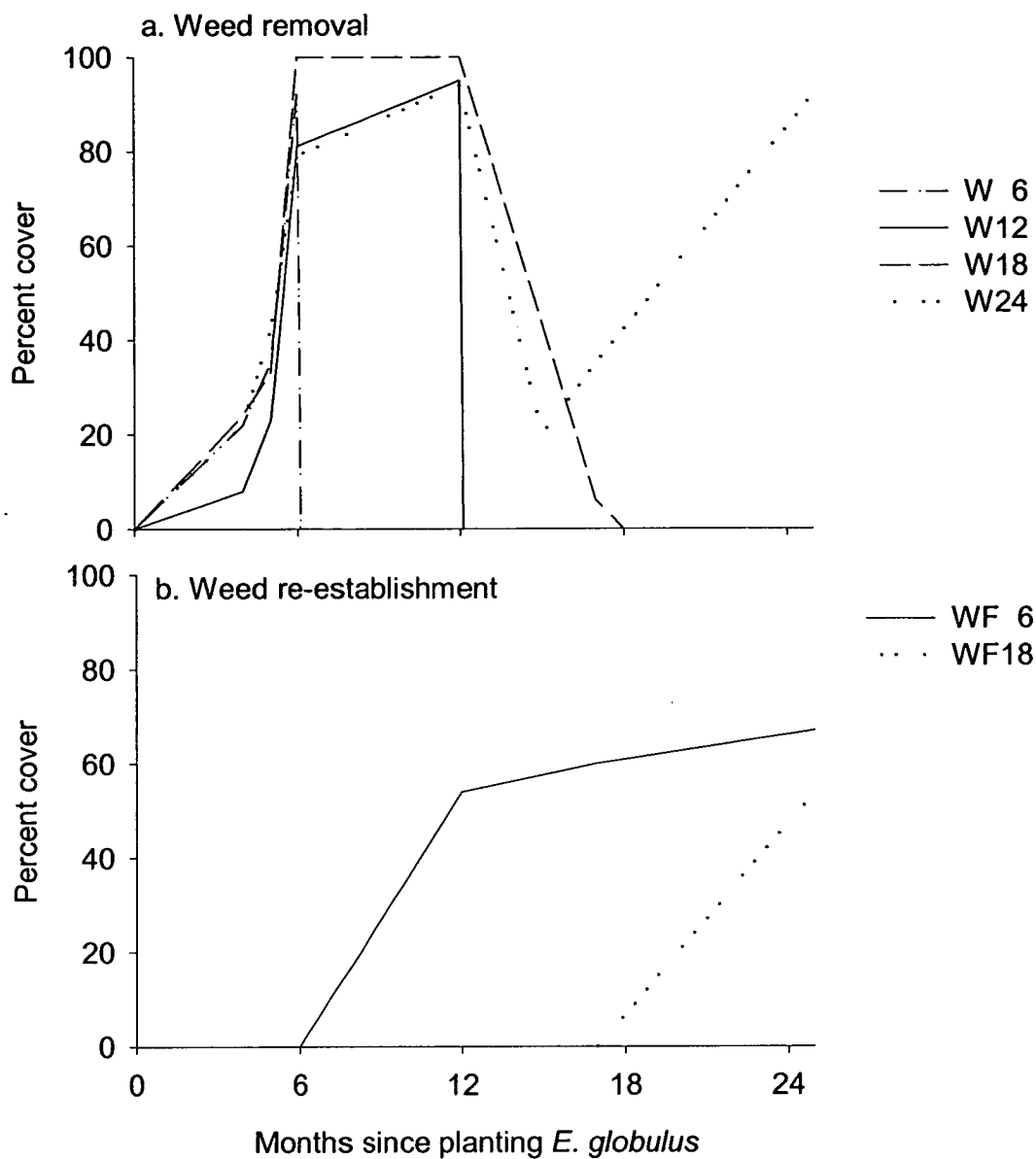


Figure 3.5 (a) *H. lanatus* presence and (b) absence periods.

3.4 Discussion

This study has demonstrated the competitive nature of *H. lanatus* as a potential grass weed. On this site, it rapidly developed into a dense, vigorous and healthy sward that dominated the weed community. *H. lanatus* also has an aggressive, fibrous root system (Nielsen 1998). Such characteristics provide a competitive advantage for site

colonisation, occupancy and resource capture (Berkowitz 1988, West and Dean 1992, Nambiar and Sands 1993, Veer and Kooijman 1997).

The pattern of growth followed seasonal patterns of light energy, temperature, water and nutrient availability (Holmes 1989) that is common among cool temperate grasses. Growth was highest during spring, lowest during winter and dormant over summer following flowering and seed set. Season of sowing affected the speed of establishment and early dominance of the species. Thus autumn sowing was more successful compared to late spring, which may be too late for this species in this climate. The low germination and survival at this time was related to high surface soil temperatures and water stress and weekly irrigation was not frequent enough to allow establishment. These results demonstrate the difficulty of establishing weeds in experiments (Richardson 1993, Maxfield *et al.* 1998).

Successful grass establishment was considered to have been achieved when ground cover approached 20%. Although a nominal figure, it was indicative of the grass behaving as a sward rather than as individuals (Figure 3.6). The time taken to reach this per cent cover ranged from 3 - 5 months after sowing. Cover approached 100% within 8 months after successful sowing. Such growth patterns are consistent with many ex-pasture sites with moderate soil water and nutrient status targeted for plantation forestry in southern Australia. In more infertile conditions, or where summer drought stress can occur, as in mediterranean climates, grass growth and dominance of the weed population can be much slower. Smethurst and Nambiar (1989) reported that it took from one to two years for *H. lanatus* to reach 20 – 30%



Figure 3.6 Re-establishment of *H. lanatus* in autumn 1997, at tree age 6 months (November 1997, six months after sowing).

cover in south-east South Australia. Under these conditions it was shown that the grass was able to compete strongly with young *P. radiata* for soil nitrogen and water. In a similar environment, *A. vulgaris* at 5 – 10 % cover induced high moisture stress in young *P. radiata* (Nambiar and Zed 1980) during the first summer after planting. Grass growth in the tropics can be much faster, and 100% cover can be reached in 2 – 4 months (Little and van den Berg 1999).

The availability of soil nitrogen was a major factor affecting the growth of *H. lanatus*. Natural levels of soil nitrogen were low (0.10% total N in the surface soil) due to low organic matter and sandy soil, and grass growth was slow and less vigorous in the unfertilised treatments. This was particularly evident in Block 3 under low irrigation. Symptoms exhibited by the grass were consistent with N

deficiency: small chlorotic leaves, and reduced tillering and leaf elongation (Whitehead 1995). When N fertiliser was applied however, *H. lanatus* responded very strongly. Shoot growth rapidly increased, leading to increased light interception and above-ground dry mass production. In common with other grass species, these responses demonstrated the importance of N supply to the growth and development of *H. lanatus* (Whitehead 1995).

A common characteristic of vigorous grasses is a large fibrous root system. This provides a strong competitive advantage for the capture and uptake of soil resources (Berkowitz 1988, Nambiar 1990, Veer and Kooijman 1997). In plantation forestry, it is widely recognised that a large proportion of applied fertiliser is captured by grasses at the expense of young tree seedlings, unless there is adequate weed control (Waring 1972, Squire 1977, Flinn *et al.* 1979, Smethurst and Nambiar 1989, Woods *et al.* 1992, Richardson 1993). In agricultural studies, rates of N recovery from applied fertiliser are often in the range 65 – 70% (Whitehead 1995) while that of young tree seedlings is often much lower. Nambiar and Bowen (1986) reported uptake ranged from 6 – 18% in a young *P. radiata* stand in the absence of weeds. The capacity for uptake of N is much greater for grasses than other crops, and under favourable conditions, can be more than 500 kg ha⁻¹ year⁻¹ (Whitehead 1995). Daily rates of uptake, however, vary with season, stage of growth and time since fertiliser application. In un-defoliated grass, N-uptake rates are at a maximum during the vegetative stage of growth in spring, peaking just prior to the reproductive stage (Whitehead 1995). The largest responses in this experiment occurred during times of peak growth in spring, although smaller responses were also obtained in autumn and winter.

The dominance of *H. lanatus* over the weed population demonstrated the strong competitiveness of the species. Many studies have shown how the growth and development of broad-leaved pasture plants such as clover (*Trifolium* spp.) (Harris 1971, Turkington 1990, Dear and Cocks 1997) and *A. vulgaris* (Nielsen 1998) is reduced in the presence of grass. This is a common occurrence, especially in un-defoliated pastures (Tilman 1990, Whitehead 1995) and can be particularly evident under conditions of high fertility.

The interrelationship between above- and below-ground competition was influenced by resource availability (Casper and Jackson 1997). The rapid shoot growth in response to high N-availability meant that competition for light became important (Mamolos *et al.* 1995) and resulted in suppression of low growing plants such as *A. vulgaris*. This highlights the importance of canopy architecture, which often determines the outcome of grass competition (Wetzel and van der Valk 1998). In a study of tall grass encroachment into dry native-dune grasslands, the short stature native grasses were suppressed due to low light (Veer and Kooijman 1997). In pot experiments, Nielsen (1998) found that *A. vulgaris* was eventually smothered by shoot dominance of *H. lanatus*, though it was recognised that below-ground competition would also have been a factor, as *A. vulgaris* is sensitive to direct competition for water and nutrients (Smith 1975). Fertilisation of young tree seedlings without adequate control of grasses often leads to overtopping and suppression due to vigorous grass leaf development (Flinn *et al.* 1979). Overtopping can be a particular problem during the spring growing season (Lewis and Ferguson 1993). It was these strong suppressive characteristics, along with the ability to grow

well on relatively infertile soils, that has promoted the inclusion of *H. lanatus* in covercrop applications for suppression of woody weeds in young *P. radiata* plantations (West and Dean 1992).

Competition for soil water has been identified as a major factor in the suppression of broad-leaved species, especially by summer-active grasses (Dear and Cocks 1997). The amount of available soil water during spring can determine the effectiveness of grass competition (Whitehead 1995). *H. lanatus* is mainly summer-dormant (cool season grass) but its vigorous growth during spring probably contributed to a soil water limitation during early summer. This is suggested by the earlier onset of flowering, seed set and maturity in fertilised than unfertilised grass (Figure 3.4a) that was associated with increased demand for soil water and higher biomass production. In wheat (*Triticum* spp), increased early growth rates induced by nitrogen fertiliser, led to more rapid extraction of soil water, leading to early ‘hay off’ when water became limiting (Baldock and Leonard 1998). Irrigation of pastures has been shown to increase productivity and can be additive to the effects of N-fertiliser (Whitehead 1995). However, in this experiment, the response of *H. lanatus* to high irrigation was small, and was only apparent in the unfertilised plots in Block 3. In this block, under low irrigation, the growth of *H. lanatus* was poorer in unfertilised treatments, where both water and nutrient availability was low.

Because of its perennial habit and ability to rapidly establish a dense, vigorous, sward with a high demand for site resources, *H. lanatus* was a strong competitor for site resources. The competitive interactions were dependent upon site resource levels, especially soil N. Favourable soil water and nutrient availability promoted

high growth rates. The combined effects of above- and below-ground competition meant that the 'zone of influence' (Costantini 1989, Little *et al.* 1997) of this grass, was very large compared to the other main species, *A. vulgaris* and young *E. globulus*. Where water or N was limiting, shoot growth of *H. lanatus* was reduced, allowing the coexistence of *A. vulgaris*. However, under these conditions, it was expected that competition for soil resources would be the predominant interaction.

3.5 Conclusions

H. lanatus is a strong competitor for site resources (light, water and nutrients) and it is likely that several of these resources were competed for simultaneously (Forbes and Watson 1992) at an intra - and inter - specific level, and both spatially and temporally. The competitive interaction between *H. lanatus* and other species was related to soil resource availability and season of growth, and their above- and below-ground interrelationship. In unfertilised treatments, grass growth was reduced, which enabled the continued presence of *A. vulgaris*. Competition for light was therefore reduced, however competition for water and nutrients would still have been important. In treatments where N-fertiliser was applied, leaf area of *H. lanatus* rapidly increased along with above-ground dominance, strongly suppressing the smaller broadleaved species such as *A. vulgaris*. This increased above-ground growth would also have led to increased demand for below-ground resources such as water. The strong response to applied N suggests that it was the main resource limiting the growth of *H. lanatus*. The relationship between site resource availability and competitive interactions between *H. lanatus* and young *E. globulus* is now investigated in Chapter 4.

4. Impact of timing and duration of grass control on *E. globulus* growth

4.1 Introduction

In this chapter the timing and duration of grass competition in a *E. globulus* plantation was investigated using Critical Period methodology. This is a procedure widely used in agriculture for examining the timing and duration of weed interference (Zimdahl 1988). It defines the period during crop development when weed control should be carried out to prevent yield loss. The form, timing and length of a critical period are determined by many interacting factors, including resource availability, weed and crop species and management (Zimdahl 1988, Goldberg 1996).

The critical period method utilises analysis of two curves; a weed-free curve that defines the length of time that weed control must be maintained to prevent yield loss, and a weedy curve that defines the length of time weeds can remain before they interfere with crop growth. The critical period is determined by the linear distance between where tree growth declines on the weedy curve and where growth levels off on the weed-free curve. The time of equal interference (TEI) occurs where the two curves cross and is the point when yield losses are equal from either being weed-free or weedy for the preceding period (Wagner *et al.* 1999). Six hypothetical critical period models have been described by Wagner *et al.* (1996). These range from wide critical periods where growth losses are proportional to time of weed presence or where any association with weeds substantially reduces tree growth, to relationships

where the critical period occurs in early, middle or later years, and finally to situations where there may be no critical period.

Research on timing of weed control in plantations usually has involved analysis of the weed-free component of the critical period, where weed control is applied for increasing periods after planting (Lauer *et al.* 1993, Adams and Dutkowski 1995, Fremlin and Misic 1999). Less work has been done on the weedy component and the effect of increasing periods of weed presence following planting (Costantini *et al.* 1992, Little *et al.* 1997). This is due, in part, to the difficulties associated with re-establishing weed species at specific times (Richardson *et al.* 1993, Maxfield *et al.* 1998). Only one published study could be found where the two critical period components have been applied successfully to plantation trees, in this case for four northern hemisphere conifers (Wagner *et al.* 1996).

Levels of available soil water and nitrogen were manipulated through irrigation and fertiliser application, respectively, to determine the extent to which these treatments alleviated competition. Two hypotheses were tested: (1) that the competitive effect of grass weeds on the growth of *E. globulus* would be strongest during the first year, and (2) that the timing and duration of competition would be related to the levels of resource availability, in particular levels of available nitrogen.

The occupation of soil volume or space is of primary importance in below-ground competition (Aldrich and Kremer 1987) and therefore tree and weed root characteristics are important. Field investigation of roots however, has the difficulty of distinguishing between grass and eucalypt roots and of identifying roots that are

presently or potentially functional in resource uptake (Fowler 1986). In this study field observations on root distribution along with data from an un-replicated pot study are used to describe characteristics and provide an insight on the root interactions between the species.

4.2 Methods and materials

4.2.1 Measurements

The height and diameter of each tree were measured bi-monthly until age 17 months, then at 21 and 24 months of age. Measurements of stem diameter at 0.15 m above-ground (D_{15}) commenced at age five months. At age 21 months, large trees could also accommodate measurements of diameter at breast height (1.3 m) (DBH). A further measurement of height and diameter was made at 53 months (4.4 years).

At age nine months, one *E. globulus* seedling was harvested from each of five diameter classes in W and WF treatments (all N_{Zero} and I_{Low}) from biomass plots, for determination of above-ground biomass. All material was dried to constant weight at 70°C. Tree diameter was converted to basal area and regressed against biomass, to estimate total above-ground biomass ha^{-1} .

Grass and tree root systems were examined during excavation of the selected biomass seedlings above, with particular interest in lateral and vertical root distributions of both species. There was also further examination utilising clear-sided root pots (60 cm deep) (Nielsen 1998) and three un-replicated treatments under glasshouse conditions. The treatments were: (E2G0) two *E. globulus* seedlings without grass, (E2G1) two *E. globulus* seedlings with one grass plant, and (E1G2)

one *E. globulus* seedling with two grass plants (Figure 4.1). All plants were grown for three months, then destructively sampled to provide biomass data. During the study, the distribution and interaction between roots was observed.

4.2.2 Data analysis

Height and diameter (D_{15}) increments at age one and two years were calculated. The height/diameter ratio (H/D) was calculated using height and diameter (D_{15}) for the mean tree per plot. Two balanced subsets of data (Sets 1 and 2) were analysed individually. Set 1, with contrasting water and nitrogen levels was analysed as a split-plot design that included an interaction between treatments. Irrigation level (I_{Low} and I_{High}) was used as the main-plots while nitrogen (N_{Zero} and N_{High}) and weed (W , WF) treatments were used as sub-plots. Each measurement date was analysed separately. The critical period treatment subset (Chapter 2, Table 2.2) was analysed as a randomised complete block design. The growth data were analysed by ANOVA (Genstat 5 Committee 1994) using LSD's to detect differences between treatments. Data transformation (\log_{10}) was required for D_{15} and H/D to meet assumptions of normality and homogeneity of variance. Five plots were excluded from Set 1 after damage from possum (*Trichosurus vulpecula*) browsing and herbicide phytotoxicity. In Set 2, three plots were excluded after herbicide phytotoxicity. These were all analysed as 'missing plots'. Total basal area ($m^2 plot^{-1}$) was measured at age 53 months and was analysed as above.

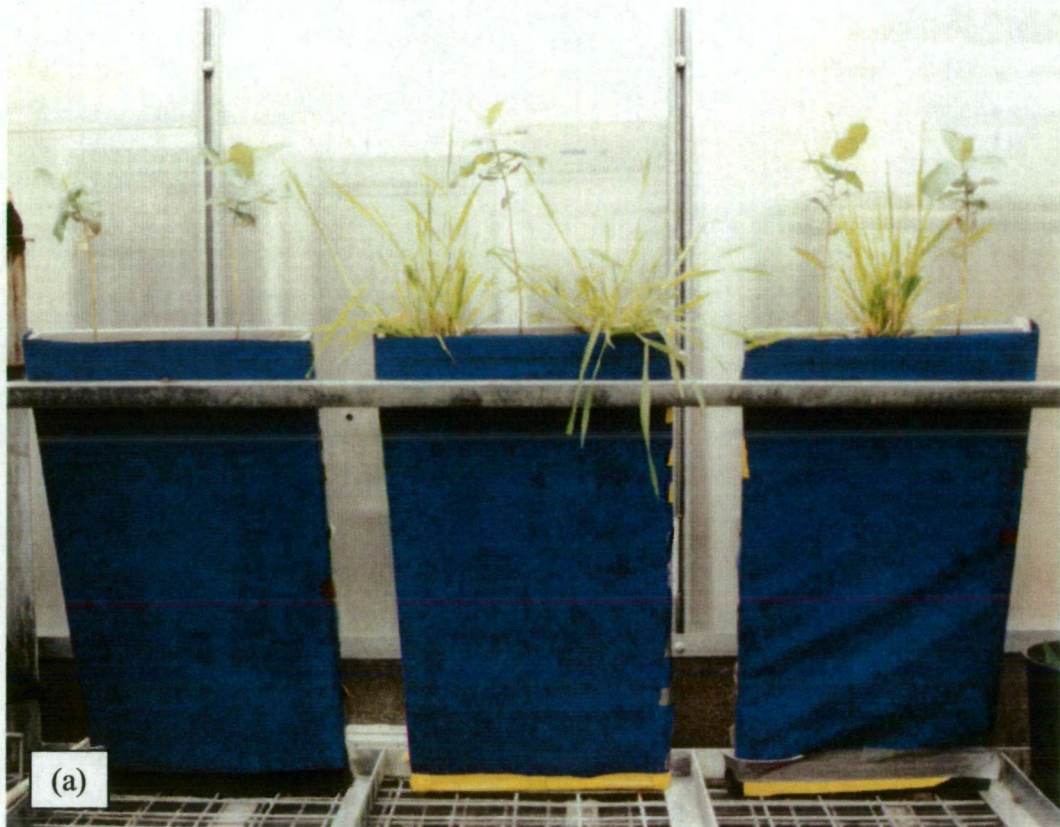


Figure 4.1 Root pot study

(a) Three treatments: E2G0, E1G2, E2G1 (E = *E. globulus*, G = *H. lanatus*)

(b) Example of root distribution in E2G1 (age two months).

The critical period of weed control was determined using regression (Cousens 1988, Hall *et al.* 1992), and solution of the equations to show when growth loss occurred. A minimum diameter reduction of 5% was used as the criterion. At age two years, weedy and weed-free curves were derived using non-linear regression of stem diameter (D_{15}) as the dependant variable, as it was the most sensitive growth variable to the effect of weeds. The equation for the weedy curve was estimated using the mean from 12 plots (4 treatments x 3 replications) while the weed-free equations used the mean of 9 plots (3 treatments x 3 replications). The Time of Equal Interference (TEI) was calculated by solving the weedy and weed-free regression equations, ie. identifying when D_{15} was equal for both curves. Data for WF12 and WF18 was excluded as re-establishment at age 12 months was unsuccessful, and there was only low impact of *H. lanatus*, sown at age 18 months, by the last time of tree measurement. W18 was excluded as the treatment was unsuccessfully implemented.

4.3 Results

E. globulus survival across the site was higher in weed-free (83 - 100%) compared to weedy treatments (54 - 97%) by the end of the two-year study. Most mortality occurred during the first 12 months, and it was generally the smaller, weaker seedlings that died. Lowest survival was in Experiment 2, where there had been high irrigation, but nil N fertiliser applied during the first year of growth.

A sustained growth response to weed removal occurred throughout the experiment. At age two years, trees in weed-free treatments were up to three times taller than trees in weedy treatments (3.9 and 1.3 m respectively) (Table 4.1, Figure 4.2a). There

was no significant response to irrigation or nitrogen measured during the first 12 months. Annual height increment was significantly greater in WF than W treatments throughout the two years. Increments were much larger in the second than in the first year in both treatments. The largest relative increase in height over the two years occurred for weed-free trees in $I_{Low} N_{Zero}$, while the smallest was for weedy trees in the same treatment. A significant ($p < 0.05$) response in W treatments to N_{High}

Table 4.1 Annual height (cm) and diameter (mm) increment to age two years. The last column gives total height and diameter growth at age two years. Within each year, treatments followed by the same letter are not significantly different ($p < 0.05$).

Treatment	<i>Age (y) and increment (y^{-1})</i>		
	One*	Two	Total
<i>Height (cm)</i>			
LI LN W	30.4 ab	66.2 a	127.5 a
LI HN W	39.8 b	100.0 ab	175.9 b
HI LN W	29.3 a	82.7 ab	141.6 ab
HI HN W	35.3 ab	115.9 b	189.7 b
LI LN WF	104.0 c	246.4 c	386.2 c
LI HN WF	95.4 c	220.2 c	347.9 c
HI LN WF	92.6 c	230.0 c	341.5 c
HI HN WF	98.1 c	179.0 c	304.1 c
<i>Diameter (mm)</i>			
LI LN W	6.1 ab	10.6 a	16.6 a
LI HN W	7.2 bc	22.3 b	29.7 b
HI LN W	5.7 a	14.2 a	19.9 a
HI HN W	7.3 c	26.2 bc	34.3 b
LI LN WF	28.7 d	51.1 d	80.0 c
LI HN WF	28.8 d	46.6 d	75.5 c
HI LN WF	26.8 d	44.5 d	71.3 c
HI HN WF	27.6 d	38.6 cd	69.9 c

*Height increment excluded initial seedling height.

Year 1 diameter increment includes seedling diameter at 1 month.

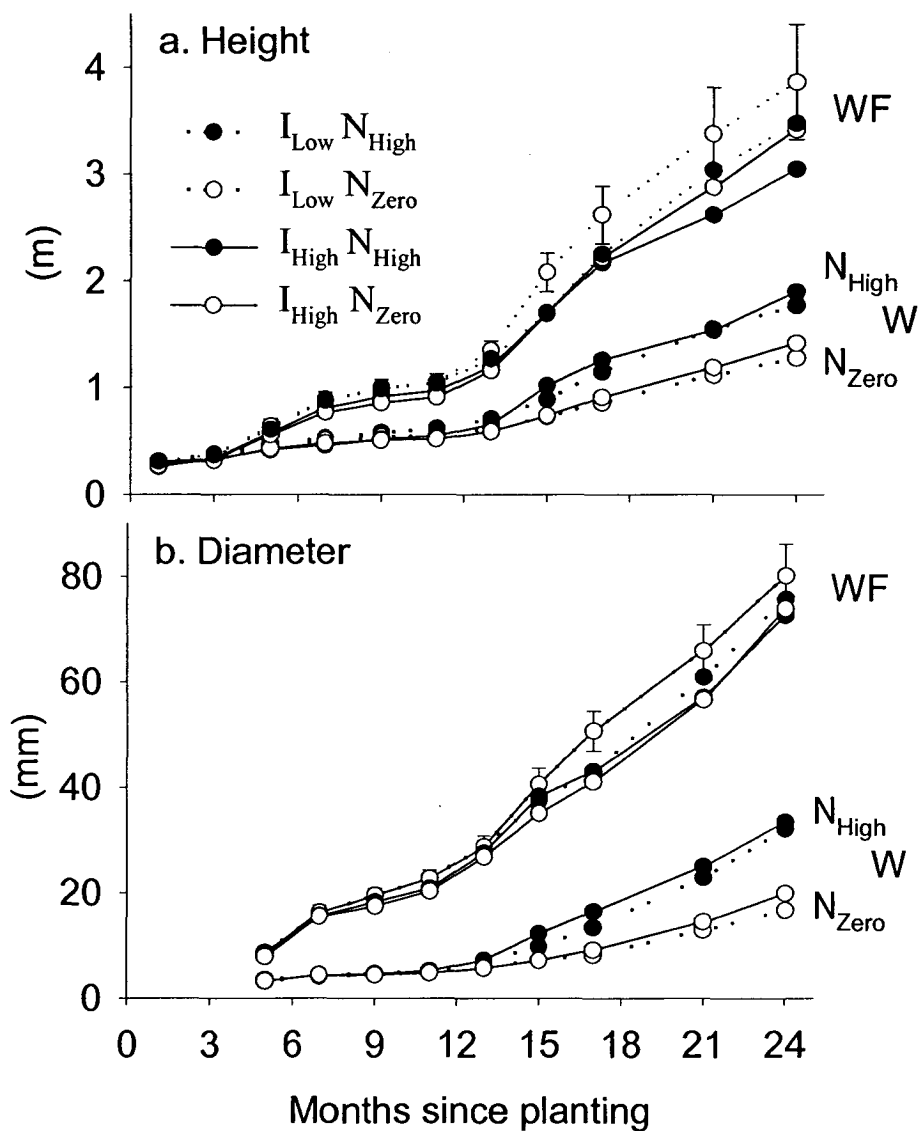


Figure 4.2 (a) Height (b) diameter at 15 cm (D_{15}) (mm) of *E. globulus* to age two years. Error bars indicate LSD's ($p=0.05$) for comparison between treatments.

commenced in the second year, while growth was reduced by N_{High} in WF treatments. Diameter growth closely followed that of height but differences between WF and W treatments were larger (Table 4.1, Figure 4.2b).

At age five months, trees growing in W treatments had smaller diameter growth relative to height than in WF treatments ($p < 0.001$). The mean H/D in WF treatments was $74 (\pm 3)$. This decreased to $46 (\pm 2)$ by age 12 months and then remained fairly constant. The mean H/D in W treatments at age five months was $131 (\pm 9)$ and this decreased to $74 (\pm 4)$ at age two years. However, the H/D in W treatments that received N_{High} decreased faster than equivalent N_{Zero} treatments after age 12 months and by age two years ratios were equivalent to WF treatments (Figure 4.3).

Above-ground dry mass at age nine months was 0.40 t ha^{-1} in WF compared to 0.03 t ha^{-1} in W treatments. Lateral root extension in W treatments was within a 30 cm radius of the tree stem with limited branching. In WF treatments, lateral roots extended beyond 2.5 m from the tree stem with heavy branching, particularly in the surface soil. Vertical root development extended to 60 cm depth in both W and WF treatments. Where trees were located in a weedy strip (buffer trees) it was observed that lateral roots travelled through a grass zone with minor branching, then upon reaching weed-free soil, they branched prolifically. Grass root development was dense in comparison and a 'mat' of roots was present in the surface 20 cm of soil, but some roots also extended down to 60 cm depth (Figure 4.4a,b). At age 12 months an excavated weed-free tree had roots extending down to 85 cm depth, while at age 28 months another weed-free tree had roots extending to 1.2 m depth, with most lateral roots within the surface 20 cm.

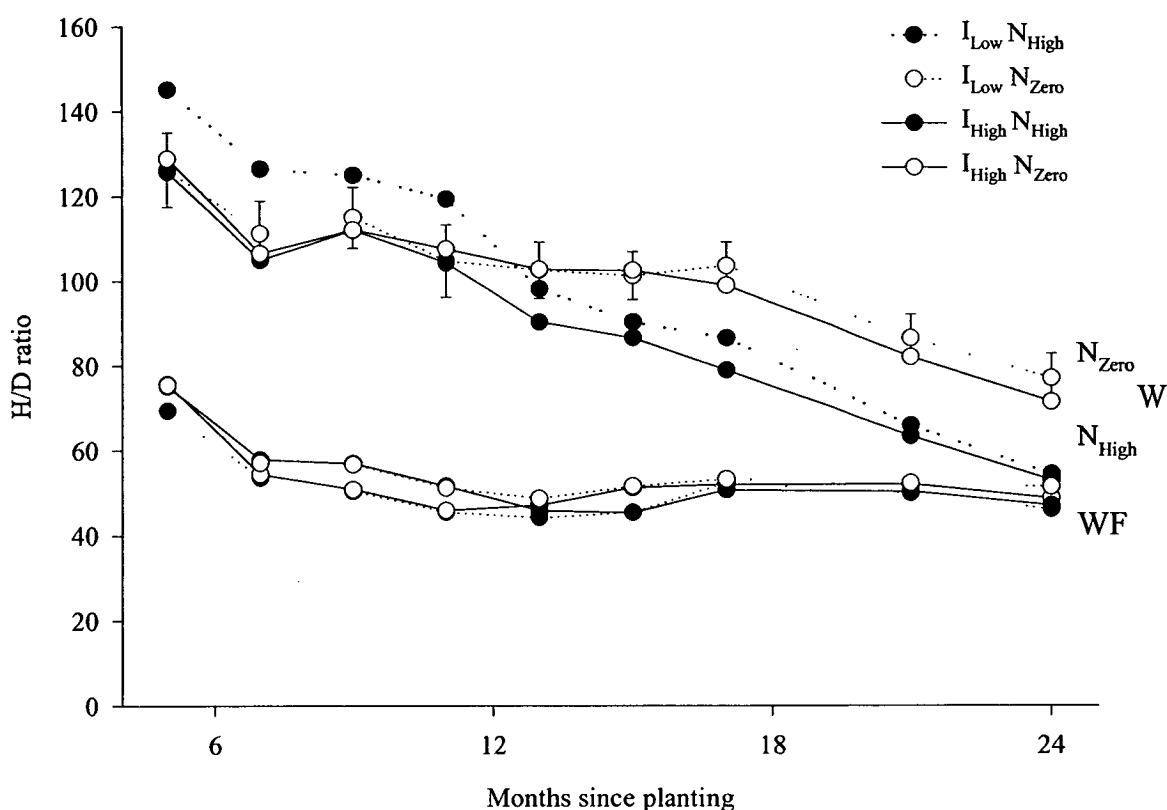


Figure 4.3 *E. globulus* height / diameter ratio. Error bars are Std dev.

The root pot study also showed that the rooting habit of both species was very different. *H. lanatus* developed a very vigorous, fibrous, multi branched structure originating from the base of the shoot, compared to the tap root system of the young *E. globulus*. Root growth and development of *H. lanatus* was very fast and roots rapidly occupied the surface soil zone before increasing in depth down the pot. There was a gradual filling up of the pots with roots over time, especially in pots containing grass. Trees growing with grass established major roots to depth in the pots but exhibited very limited branching until near the lower part of the pot. This was despite the apparent increased density of grass roots in this portion of the pots (Figure 4.5). There was very little lateral spread of the tree roots, as they were rapidly dominated

by the presence of grass roots. Tree roots growing with weeds were thin, long and appeared to be suberised early on, and they were covered along their length by very fine root hairs (Figure 4.5b). In comparison, the weed-free trees showed extensive root development, with much branching. The lateral roots were thick, white and largely unsuberised, and reflected increased activity and growth compared to trees growing in weedy plots.

Tree height between treatments was similar while diameter growth, leaf area and stem biomass of individual tree seedlings was 58%, 112% and 110% greater respectively in the weed-free plot (E2G0) than the weedy pot (E1G2). Height / diameter ratio was 114 in weed-free trees and 189 in weedy trees. Root biomass of individual tree seedlings was 3.5 times greater in the weed-free than weedy pot. In contrast, grass root biomass was 30 times greater than that of the weedy tree, and above-ground grass biomass 80% greater (Figure 4.6).

Critical period

The timing and duration of weed presence significantly affected *E. globulus* height and diameter growth ($p < 0.001$). Two years of continuous grass presence reduced height and diameter to 52% and 40%, respectively, of trees growing in entirely weed-free conditions.

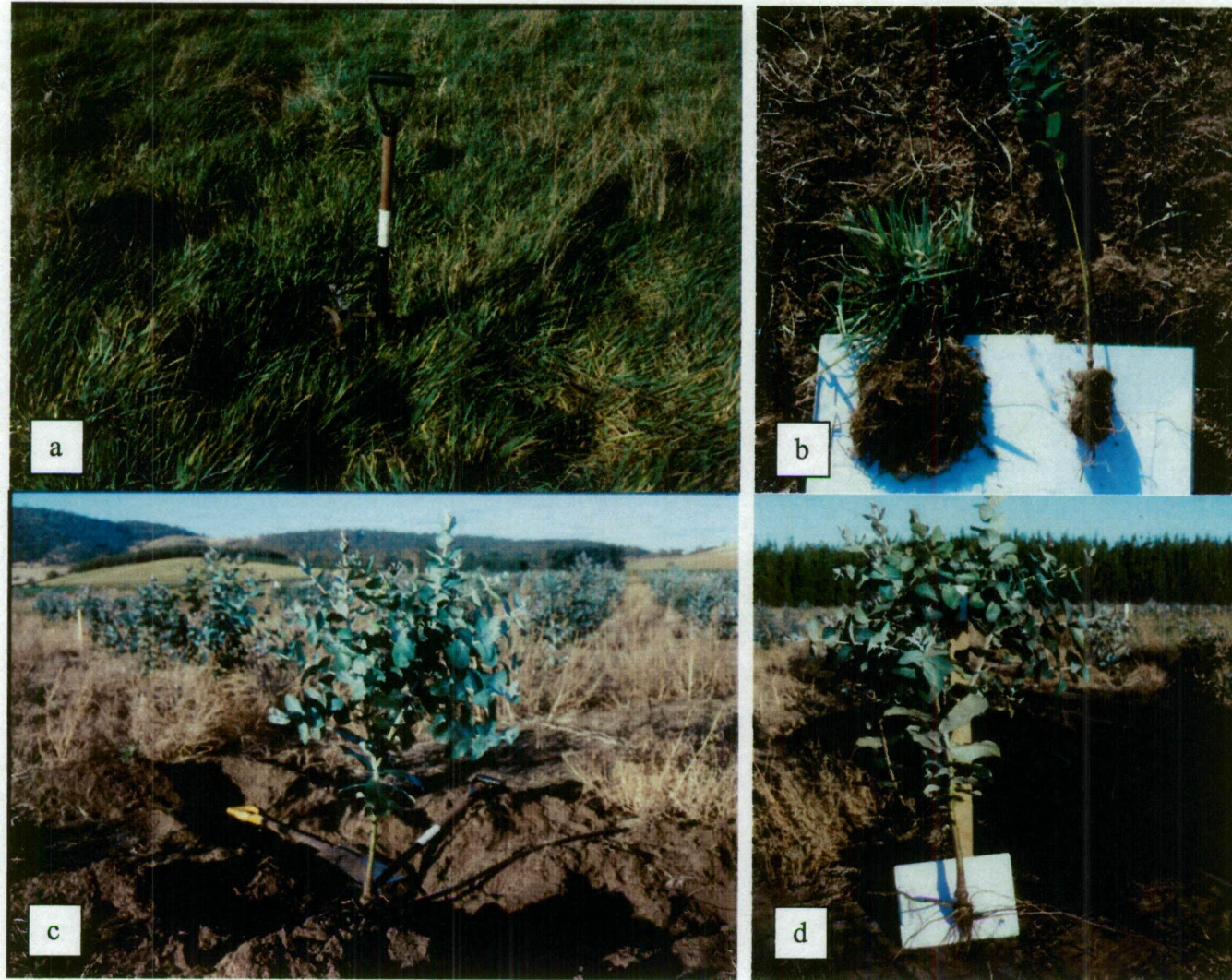


Figure 4.4 Nine-month-old *E. globulus* (a) in weedy plot (b) weed and tree root system (c) weed-free tree with extensive root excavation, and (d) cross section of root system of weed-free tree

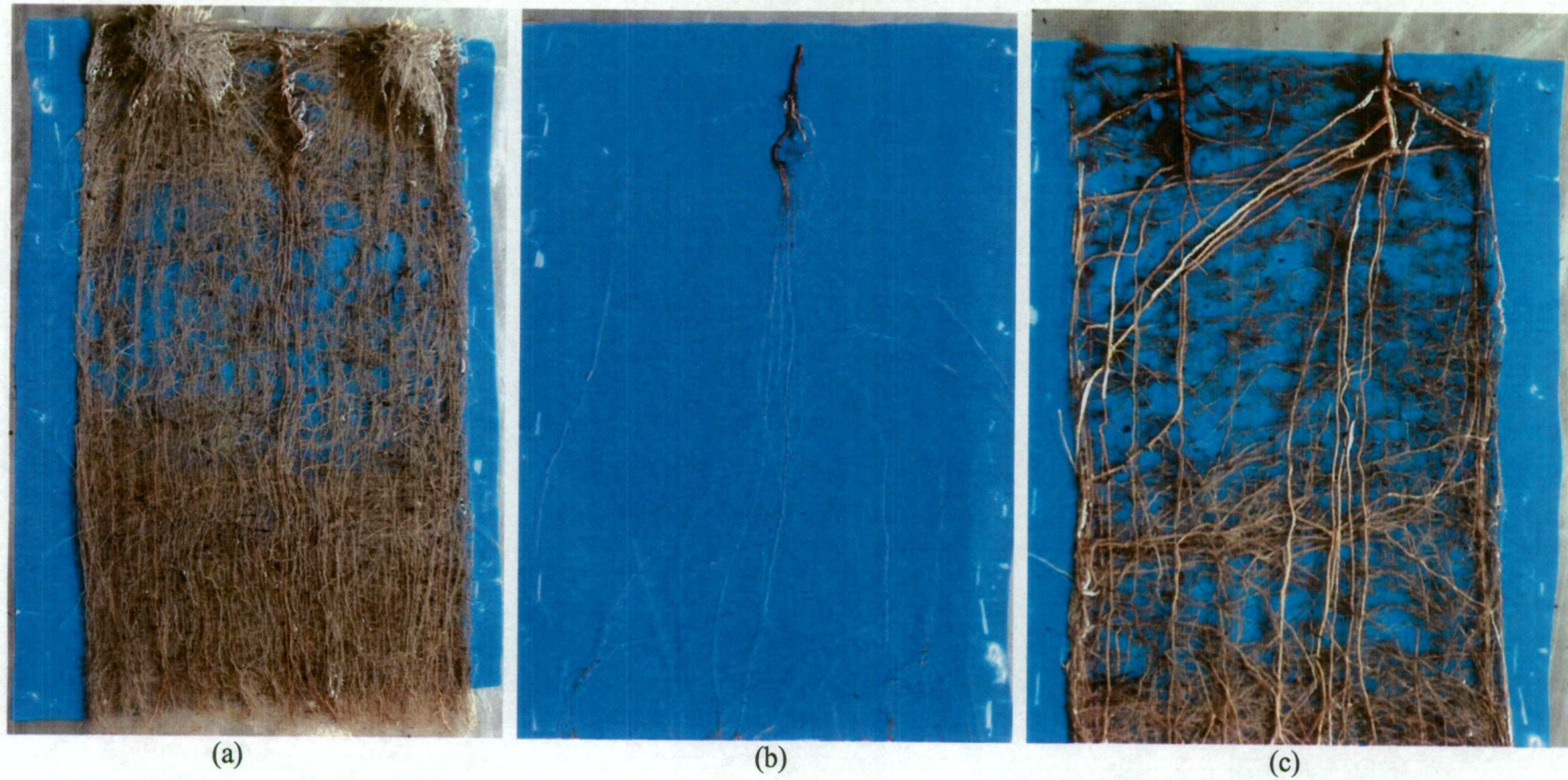


Figure 4.5 *H. lanatus* and *E. globulus* root characteristics when extracted from root pots at age three months
 (a) E1 G2: *E. globulus* seedling surrounded by roots from two *H. lanatus* plants
 (b) E1 G2: *E. globulus* seedling following removal of *H. lanatus* roots
 (c) E2 G0: two *E. globulus* seedlings in absence of *H. lanatus*

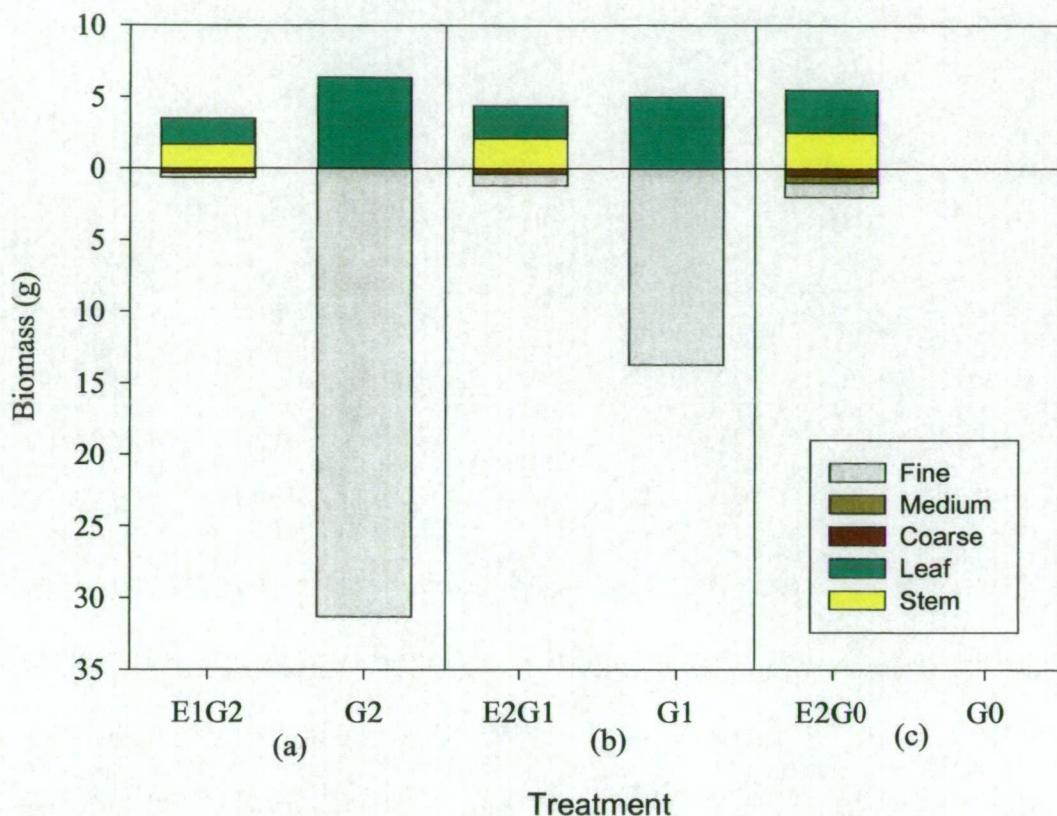


Figure 4.6 Above- and below-ground biomass of *E. globulus* and *H. lanatus* in the root pot study (age three months). Three treatments: (a) E1 G2: *E. globulus* seedling growing with two *H. lanatus* plants (dry mass by component, i.e. for single *E. globulus* and for two *H. lanatus* plants) (b) E2 G1: two *E. globulus* seedlings growing with one *H. lanatus* plant (dry mass for mean *E. globulus* seedling and for one *H. lanatus* plant) (c) E2 G0: two *E. globulus* seedlings in absence of *H. lanatus* (dry mass for mean *E. globulus* seedling where there were two *E. globulus* seedlings per root pot).

Tree growth decreased as the duration of weed presence increased (Figure 4.7). In addition, there was a significant delay in recovery of growth after the application of weed removal treatments. Trees released after six months weed presence took seven months before growth started to diverge from the later weed removal treatments. At age two years, diameter was 23% smaller in this treatment than that of WF24 trees (Figure 4.7). Trees released after 12 months grass presence took three months to commence recovery and at age two years diameter was 41% smaller than that of

WF24 trees. Where trees had grown for the full two years with grass, diameter was 57% smaller than that of WF24 trees.

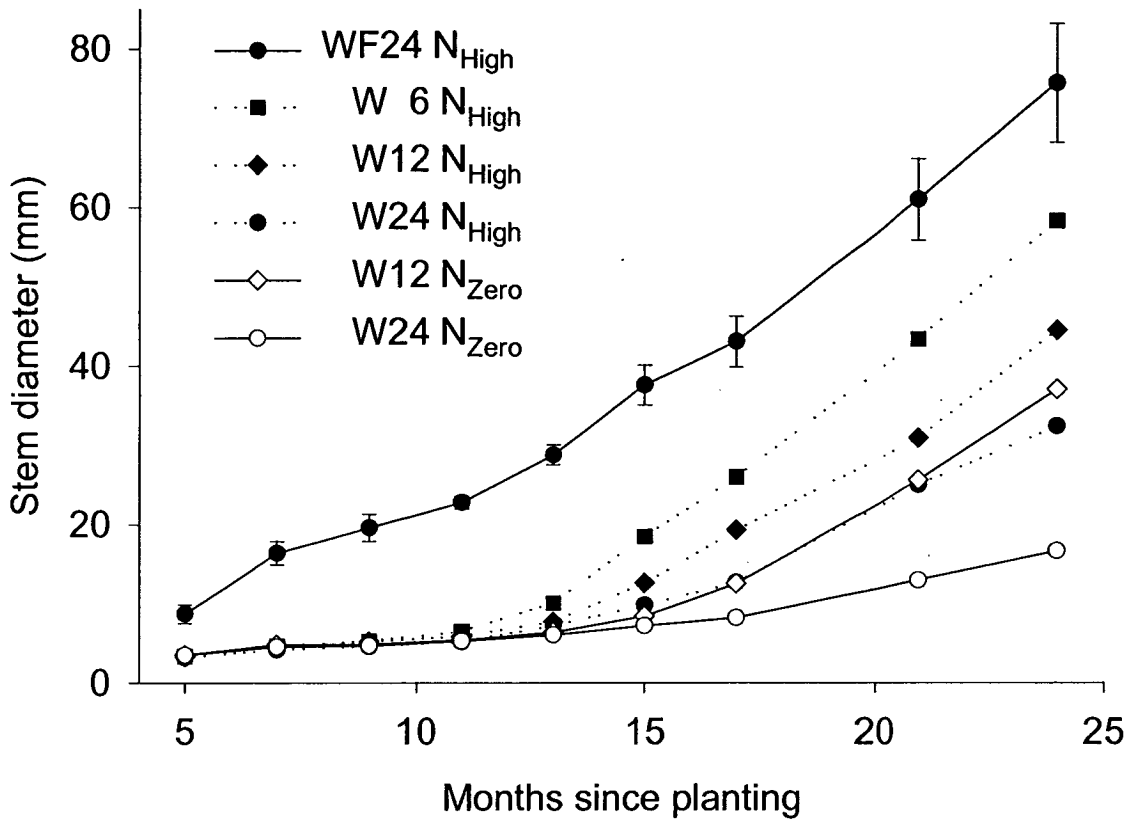


Figure 4.7 Effect of delaying *H. lanatus* removal on *E. globulus* diameter (D_{15}) (mm) growth. Error bars indicate LSD's ($p=0.05$) for comparison between treatments.

Tree recovery was delayed longer and suppressed to a greater degree in N_{Zero} treatments. At age two years, diameter growth was 50% and 80% smaller in N_{Zero} than N_{High} in W and WF treatments, respectively (Figure 4.7). At age 4.4 years this difference was still present. Basal area ($m^2 plot^{-1}$) for N_{Zero} W24 was 33% lower than N_{High} W24 and 63% lower than N_{High} WF24 (Table 4.2).

Table 4.2 Mean plot basal area (m²) at age 4.4 years. Treatments appended by the same letter are not significantly different ($p < 0.05$).

Treatment	Fertiliser application	
	N _{Zero}	N _{High}
W6		0.199 cd
W12	0.147 abc	0.193 cd
W24	0.085 a	0.127 ab
WF6		0.191 bcd
WF12	0.242 de	0.201 cd
WF18	0.278 e	0.179 bcd
WF24		0.227 de

Re-establishing grass at six months after planting resulted in a 20% smaller diameter at age two years than that of WF24 trees. Re-establishment of grass at 18 months did not affect tree growth at age two years.

Of the critical period curves (Figure 4.8) the weed-free curve was best described by a concave exponential function.

$$\text{Weed-free diameter} = 89.2 - 59.9 (0.9398)^t; \quad r^2 = 0.81 \quad (4.1)$$

where t = time in months.

The weedy curve was described by a convex negative exponential function.

$$\text{Weedy diameter} = 12.7 + 61.3 (0.9455)^t; \quad r^2 = 0.84 \quad (4.2)$$

The weed-free curve shows that diameter growth increased with increasing duration of weed-free conditions. Maximum diameter growth was approached (80%) after approximately one year of weed control. The weedy curve shows that diameter growth declined immediately after planting in the presence of grass and that this decline was still apparent at age two years. Solving these two equations, and using a minimum 5% reduction in diameter growth compared to that in continuous weed-free conditions as the criterion, the critical period of weed control at this site was from planting to age 20 months. Successful grass establishment was considered to have occurred when ground cover approached 20%. Although an arbitrary figure, this was indicative of the grass behaving as a sward rather than as individual plants. The time taken to reach this per cent cover ranged from 3 – 5 months after sowing. The points at age 10 months on the WF curve indicate when the six month re-establishment of *H. lanatus* started behaving as a sward and therefore influencing tree growth. Re-establishment at age 12 months was unsuccessful, while there was only low impact of *H. lanatus* sown at age 18 months, by the last time of tree measurement.

At age 4.4 years, using basal area ($\text{m}^2 \text{ plot}^{-1}$), the W and WF curves were also best described by exponential functions, though they had poorer fits ($r^2 = 0.44$ and $r^2 = 0.55$, respectively). Solving the equations as above showed that the critical period occurred from 4 months after planting to 18 months after planting, a similar result to that obtained at age two years (0 – 20 months after planting). Mortality was higher in the weedy treatments, while mean tree diameter was similar between treatments. Evaluation of basal area per plot showed that differences between treatments remained large. It was also clear that another important outcome from weed

competition is not only lower total production but also high variability of the crop due to mortality. Growth differences between weedy and weed-free treatments were still apparent at age 4.4 years even though treatments had ceased over two years previously (irrigation and nitrogen fertiliser) and the influence of grass would have declined.

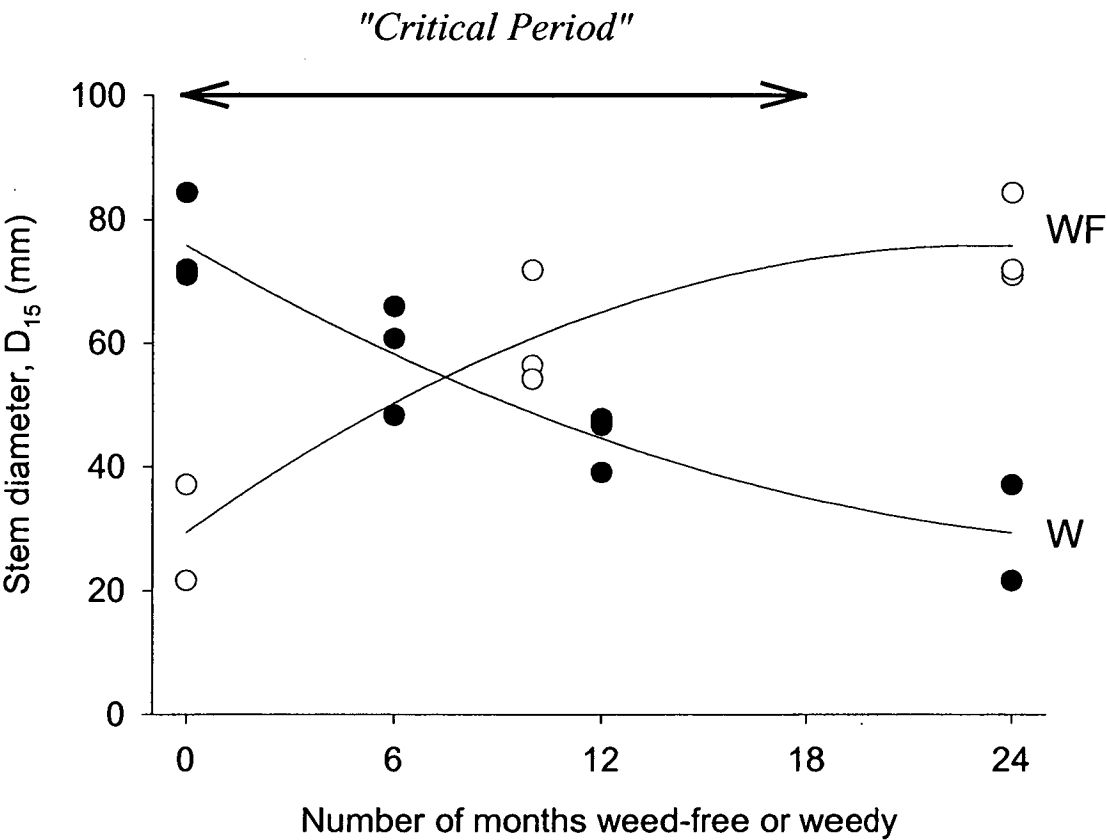


Figure 4.8 The critical period of *H. lanatus* interference with *E. globulus* based on stem diameter at 24 months (all receiving I_{Low} and N_{High}).

The weed-free trees would have been experiencing increased intraspecific competition for soil water and nutrients, therefore growth rate would be declining relative to the weedy treatments that still had larger growing space per tree and had not closed canopy. The occurrence of large gaps in several plots indicated that it will be several years before canopy closure occurs in the weedy treatments, whereas the weed-free treatments fully occupied the site.

The TEI for growth at two years (Figure 4.8) occurred at 8 months, indicating that the same yield can be achieved at age two years (equivalent to 60% of WF24 trees) by having weed-free conditions from planting to age 8 months, or by having 16 months of weed-free conditions from age 8 months to age two years.

Rate of nitrogen application (Experiment 2)

E. globulus growing in weeds receiving high irrigation responded strongly to increasing rate of nitrogen application ($p < 0.05$). At age two years there were three groups of responses to the five rates of application (Figure 4.9). There were two high growth responses to the highest rates (N_{800} and N_{1200}), two low responses to N_0 and N_{200} , and an intermediate response to N_{400} . The intermediate and high responses were not significantly different from one another ($p > 0.05$) and there was only a small increase in diameter for N_{1200} over N_{800} . The N_0 and N_{200} treatments were much lower compared to the other rates and were not significantly different ($p > 0.05$). The N_{800} rate was similar to that applied in the N_{High} treatment in Experiment 1 (900 kg N ha^{-1}) except that no nitrogen was applied during the first year of tree growth, however responses were similar between the two experiments.

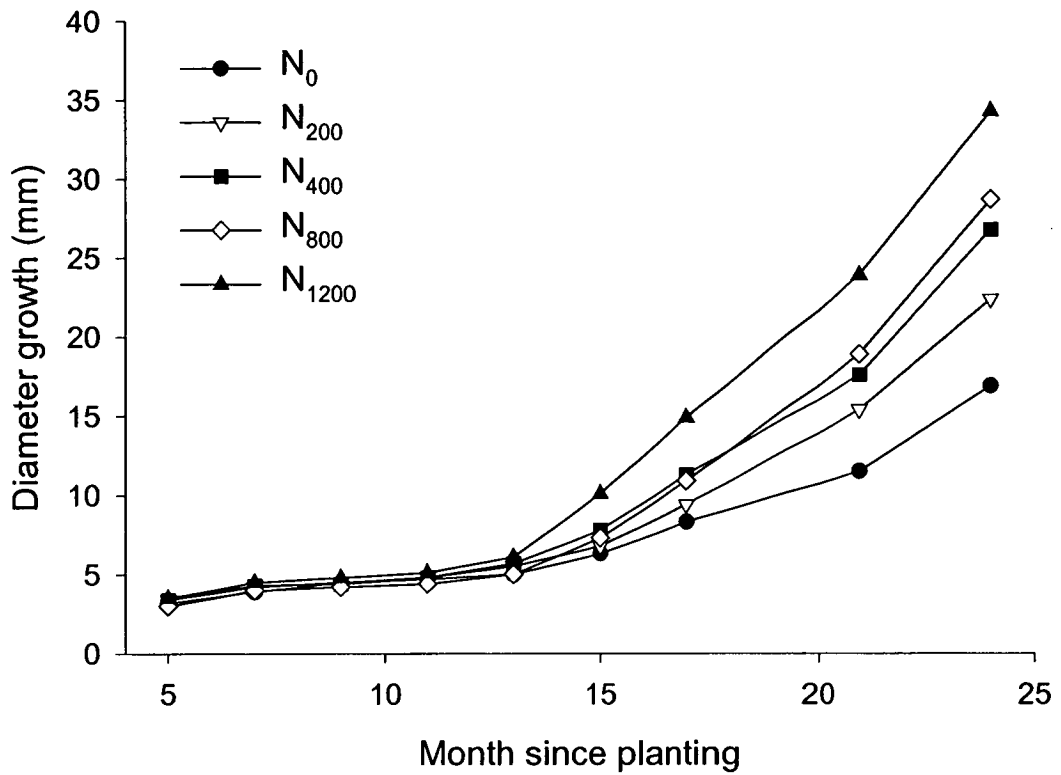


Figure 4.9 *E. globulus* response to rate of nitrogen application in presence of weeds and high irrigation ($I_{\text{High W}}$)

Tree health and other factors affecting growth

A number of growth problems became evident in some treatments and locations across the site during the study. Some were temporary problems and some were long term in nature. Temporary problems included browsing damage by possums in two plots in Block 3, and strong wind damage (toppling) in weed-free treatments across the site during the first 6 months of growth. Long-term problems involved herbicide damage to *E. globulus* in several plots and this required exclusion of these plots from further analysis. In addition, symptoms consistent with micro-nutrient deficiencies (copper and zinc) were apparent during the second year of growth along with some

evidence of salinity. In both cases mild to severe symptoms occurred in weed-free treatments, while no symptoms were evident in the slower growing weedy treatments. The main outcome of these problems was a reduction in the potential growth of weed-free trees. Therefore, maximum differences between weedy and weed-free treatments were not demonstrated.

4.4 Discussion

H. lanatus caused severe and sustained interference with the growth of *E. globulus*. Both height and diameter of the crop species were markedly suppressed during the first two years. It was also clear that leaf area development of trees growing with weeds was severely reduced. Consistent with earlier studies (Revell 1976, Schumann 1992, Fremlin and Misic 1999), up to 80% of the diameter growth of the trees at age two years was attributed to weed control during the first year. However, due to the vigour and dominance of the grass, weed control during the first half of the second year also contributed to the maximisation of early tree growth. The duration of grass weed control is therefore important for *E. globulus*.

Fremlin and Misic (1999) also found that the importance of grass interference in *E. globulus* plantations in Western Australia was strongest during the first one to two years after planting but that the duration of weed control was dependent on soil and site conditions. Sites with high resource availability and growth potential were less likely to respond to second year control, especially where good weed suppression had occurred in the first year. By the end of the second year of growth the trees are usually of sufficient stature (2 – 4 m in height in eucalypt plantations in southern Australia) to exert a suppressive effect on weed growth. In tropical hardwood

plantations, with very high rates of tree growth, weed control may be required in the first year only (Chong and Jones 1982). Little and van den Berg (1999) reported that *E. dunnii* in South Africa required weed control for only the first three months after planting before it dominated the site. On water- and nutrient-limited sites or with slower growing tree species, the length of time for weed interference will be longer (Wagner *et al.* 1999), dominance of the site will be delayed and therefore the duration of weed control will need to be extended.

There was a strong response in tree growth to N_{High} in the presence of weeds, especially during the second year, suggesting that availability of, and competition for, nitrogen was limiting tree growth. Competition by trees for mobile nutrients, particularly nitrate, is intense with grass species, which have a very high capacity for its uptake and utilisation (Eissenstat and Mitchell 1983, Smethurst and Nambiar 1989). Trees were more suppressed in N_{Zero} treatments, than in N_{High} treatments, even though grass growth was also less vigorous. The application of high rates of fertiliser (900 kg N ha^{-1}) was unable to offset lost tree growth (Goode and Hyrycz 1976, Squire 1977, Balneaves 1982, Qasem 1992, Woods *et al.* 1992). However, in two – to three – year – old plantations of *P. radiata*, nitrogen fertiliser did largely compensate for the detrimental effects of weeds on tree growth: this was attributed to rapid establishment and non-limiting levels of available water (Woods *et al.* 1992).

The vigour and dominance of *H. lanatus* was reflected in the high rates of biomass production ($9 - 14 \text{ t ha}^{-1}$) compared to *E. globulus* (0.03 t ha^{-1}) at age nine – ten months. Dry mass of trees from WF treatments at the same age was 14 times larger (0.43 t ha^{-1}). In another Tasmanian trial, *E. globulus*, growing on a weed free,

nutritionally poor soil had 0.03 – 0.20 t ha⁻¹ above-ground dry mass at age 10 months. A closely related species, *E. nitens*, growing on a fertile soil, had 0.30 – 0.40 t ha⁻¹ dry mass (estimated from Cromer *et al.* 1995).

Good lateral root development is essential for tree seedling growth (Nambiar 1990). Vigorous grass growth was associated with dense root development, particularly in the top 20 cm of soil, and a restriction of the lateral extension of tree roots. Thus the grass had a competitive advantage for nutrients (Aldrich and Kremer 1997). Both species had roots at 60 cm depth indicating that they had ready access to soil moisture via the shallow water table. The dominance of grass roots in surface soils has been widely demonstrated and the restriction of lateral root growth in the presence of grass has been reported for other tree species (Smethurst *et al.* 1993, Collet *et al.* 1996b, Ludovici and Morris 1998).

H. lanatus has the ability to rapidly exploit the soil and suppress the growth of other species. In a study using clear-sided pots to investigate root competition between *H. lanatus* and *A. vulgaris*, Neilsen (1998) showed that the length of grass roots was much greater than the broadleaf. Ludovici and Morris (1998) showed that *P. taeda* seedlings had reduced root elongation rates and depth when in competition with grass, however, bud initiation and mortality was not affected. And in another study using pots, the lateral root extension of *P. elliotii* was reduced in the presence of grass (Smethurst *et al.* 1993). In the present study, both *E. globulus* and *H. lanatus* had rapid root growth and development in the sandy soil, with the exception of lateral roots of trees, which were very restricted by the grass roots. It was clearly observed that the grass roots occupied a far greater soil volume, with a root length

density many times greater than tree seedlings. Nambiar (1990) reported that young *P. radiata* had root length density (L_v , cm cm^{-3}) equivalent to 2% of that of grass L_v occupying the top 10 cm soil depth, and 0.3% at 20 – 30 cm depth. Lockaby *et al.* (1988) reported that young *P. taeda* had only 0.3% of the L_v compared to grasses in the volume of soil containing the root bole. Root competition is considered to be symmetrical and proportional to size of root system (Aldrich and Kremer 1997) and these figures demonstrate the huge advantage that grass has over young establishing trees in terms of total surface area for soil exploration and nutrient and water absorption (Smethurst *et al.* 1993). This does not account for mycorrhizal associations of young trees that would assist uptake. However, based on the large differences in root biomass and L_v between the two species, it is hypothesised that lateral root growth of young trees was restricted by the reduced availability of water and / or nitrogen due to depletion by the grass.

Where N-fertiliser was applied in weedy treatments, the slow tree growth response was probably associated with the restricted tree root development, however, nitrogen immobilisation and leaching also may have been important factors (Fisher and Binkley 2000). The larger response to N-fertiliser during the second year of growth was probably associated with more developed and extensive tree root systems capable of increased nutrient capture and uptake. As trees grow their root systems usually overcome the influence of weeds due to access to resources beyond the weed 'zone of influence' (Sands and Nambiar 1984, Costantini 1989). However, where a grass understorey is maintained for grazing (eg. silvopastoral management) competition from these weeds for surface soil resources will be ongoing (Clinton and Mead 1994a, De Montard *et al.* 1999).

Although there was no significant growth response to irrigation, there was a response to nitrogen in weedy treatments under I_{High} , indicating a water x nitrogen interaction in the surface soil (Sands and Nambiar 1984, Ludovici and Morris 1998). This suggests that trees were under nutrient stress due to lower water availability in the surface soil. Higher water availability provided by I_{High} could have increased nitrogen mineralisation, and enhanced root uptake of N via diffusion and mass flow (Nambiar and Sands 1993, Kozlowski and Pallardy 1997).

The level of soil fertility influenced the speed of recovery of tree growth after post-planting application of weed control. Trees in N_{High} treatments responded faster than trees in N_{Zero} treatments, indicating that access to increased levels of available nitrogen increased growth. In addition, weed control applied in spring when tree growth was increasing was associated with faster recovery than in autumn, when growth was decreasing. This also highlights that *E. globulus* growing with grass has been rendered both morphologically and probably physiologically unprepared to take full advantage of future favourable conditions (Kirongo *et al.* 2002). This is largely related to the reduced leaf area and root system development of these trees in comparison to weed-free trees.

In agriculture, the critical period method has been employed in a wide range of weed - crop situations within a single growing season (Nieto *et al.* 1968, Zimdahl 1988). In forestry, competition can occur across seasons and the intensity of the plant interactions can change with time. In addition, agriculturalists are often more concerned with the economic (eg. fruit, roots) rather than the total plant yield, and it

is common that there are periods in a crop cycle when weed competition can be tolerated (Bleasdale 1987). In a forestry or tree crop context, this has been demonstrated in tree seedling nurseries: *Pinus strobus*, (Irvine *et al.* 1995); *Hevea brasiliensis*, (Suryaningtas and Terry 1993); *Elaeis guineensis* Jacq., (Iremiren 1986). Nevertheless, during field establishment, early weeds are considered to be the most damaging and, as found in this study, where total plant yield is important, early and sustained weed control is required until crop dominance occurs.

A critical period study of four northern-hemisphere conifers to age five years, suggested that weed presence during the first year of growth could be tolerated without loss in yield, though poor vegetation growth may have contributed to this result. The relatively slow growth and tolerance of conifer species to competition from weeds may also be a factor (Wagner *et al.* 1999). In addition, the use of orthogonal contrasts to determine the critical period (Wagner *et al.* 1999) is dependent on the precision of the estimate (i.e. replication and number of time intervals) and large growth losses can occur before they are determined as being statistically significant (Cousens 1988). In the present study, the use of regression analysis to determine the critical period (Cousens 1988) also has potential weaknesses, in this case missing data and the low number of time intervals on which the curves, especially the WF curve, are based. This makes it difficult to determine the levelling off of the WF curve. However, both curves are consistent with other critical periods for a wide range of species (Wagner *et al.* 1999). Earlier observations between one and six months of age would have allowed a test of early yield decline for the W curve (R Wagner pers comm.).

Maximising early growth of *E. globulus* in this study required weed control from planting through to age 20 months. There was no early period after planting when weeds could be tolerated by the young eucalypts. This relationship still held at age 4.4 years, two years beyond cessation of treatments. This is probably due to the vigorous grass growth, effective control and maintenance of treatments during each of the critical period intervals, and the sensitivity of the fast growing *E. globulus* to weed interference.

Where weed control was delayed after planting, tree growth was strongly suppressed compared to that realised in weed-free conditions. Delays of 6, 12 and 24 months after planting resulted in tree diameter growth that was 4, 7 and 9 months, respectively, behind that at 24 months in weed-free trees. The duration of weed control was also important as diameter growth increased rapidly when the duration of weed-free conditions was increased. Re-establishment of weeds after planting slowed tree growth, but after 12 months of age, the trees were sufficiently well established to tolerate some grass presence. After 20 months, there was no further growth benefit from continued weed control. The TEI at age 8 months showed that if weed control is delayed until eight months after planting, it will take a further 16 months or twice as long for weed control to compensate for the accrued growth losses. This however, does not account for losses due to mortality while in the presence of weeds. In their five-year study of four conifers, the TEI occurred between age one and two years after planting (Wagner *et al.* 1999).

The timing and duration of weed – tree interactions is influenced by the time of weed emergence relative to the degree of tree establishment, the rates of growth and

development of both species, their individual effects on and response to resource availability, and season and management (Zimdahl 1988, Goldberg 1996). This study has demonstrated the importance of resource availability, particularly soil nitrogen, in weed – tree interactions. In addition, the critical period method provides a useful way of examining the timing and duration of interference between a vigorous grass and young fast-growing eucalypts. It has provided a definition of the period when weeds should be controlled to avoid tree growth losses. Linking critical period analysis to data on resource characteristics, availability and processes would enable greater understanding of the underlying competitive mechanisms and is the objective of later chapters.

4.5 Conclusions

The study demonstrated the interacting effects of timing of weed control and soil water and nitrogen supply on the dynamics between grass and young *E. globulus*. The trees were very sensitive to competition from *H. lanatus* and large growth losses were incurred with height and diameter growth of weedy trees being 52% and 40% of weed-free trees, respectively, at age two years. Most growth losses occurred during the first year. Delaying grass control is very detrimental to *E. globulus* growth as grass competes from an early age in the young plantations. The critical period of weed interference was from planting to age 20 months at this site, under conditions of high nitrogen fertiliser application. At age 4.4 years, treatment differences were still present, indicating that the period required for weed control determined at the earlier age (two years) was still valid.

High applications of nitrogen improved tree and grass growth under weedy conditions but did not compensate for losses, while under weed-free conditions it caused some growth suppression, and induced micro-nutrient imbalance. The best growth was achieved in un-fertilised weed-free trees. Watering did not significantly affect tree growth in the presence or absence of grass, however in weedy plots, when applied in combination with nitrogen fertiliser, the growth of *E. globulus* improved considerably. It is evident that competition for nitrogen occurred between the trees and the grass at this site, and that extra water makes nitrogen more available.

It was clear that differences in root systems are important. Lateral root growth of *E. globulus* was severely restricted in weedy plots while grass roots occupied a much larger soil volume with an apparent much greater root length density. Therefore, it is hypothesised that capture and uptake capacity of the grass was superior to the restricted *E. globulus* root system.

The effect of soil water and soil nitrogen availability on the interaction between grass and young trees is now investigated.

5. The soil water regime under *H. lanatus* and young *E. globulus*

5.1 Introduction

Tree productivity can be directly related to level of rainfall (Whitehead 1995, Harper *et al.* 2000). However, it is the annual distribution of rainfall as well as the total amount, in conjunction with soil water storage and vapour pressure deficit that control the pattern of tree growth (Mitchell and Correll 1987, Boomsma and Hunter 1990, Pereira *et al.* 1989). Where summer rainfall deficits occur, and soil water storage is limited, severe drought stress in young and established plantations is common (Dutkowski 1995). The majority of *P. radiata* plantations in Australia receive $< 1200 \text{ mm yr}^{-1}$ (Booth and McMurtrie 1988), while the major expansion of eucalypt plantations during the last decade has been mainly in regions with even lower rainfall where the potential drought risk is higher. Therefore, soil water availability is considered to be the most critical limiting factor to tree growth in southern Australia (Nicolls *et al.* 1982, Boomsma and Hunter 1990, Richardson 1993).

Competition between trees and herbaceous weeds for limited soil water resources is common, particularly during plantation establishment (Squire 1977, Nambiar and Zed 1980, Sands and Nambiar 1984, Cole and Newton 1986, Boomsma and Hunter 1990, Orr and Todd 1992, Kirongo *et al.* 2002). This competition is often associated with a decline in soil water availability due to the presence of weeds (Elliot and White 1987, Crunkilton *et al.* 1992, Collet *et al.* 1996b). On sites with low soil water storage, grasses in particular with their extensive root systems, in combination with

summer rainfall deficits (Margolis and Waring 1986, Gordon and Rice 1993), can make soil water a limiting resource to young tree seedlings in many areas. As the roots of young trees are largely confined to the surface soil within the 'zone of influence' of weed roots (Nambiar 1990), drought stress can be severely exacerbated (Eissenstat and Mitchell 1983, Boomsma and Hunter 1990, Orr and Todd 1992, Perry *et al.* 1994). With control or removal of weeds, soil water content typically increases and tree water relations improve (Preest 1977, Nambiar and Zed 1980, Smethurst and Nambiar 1989, Crunkilton *et al.* 1992, Hadryanto 1994). As the tree root systems develop and access deeper soil water reserves away from the influence of the weeds, the effects of weed-induced water stress generally decrease (Sands and Nambiar 1984, Smethurst and Nambiar 1989, Clinton and Mead 1990, Kellas *et al.* 1995, De Montard *et al.* 1999).

While soil moisture deficits under weeds are common in areas that experience summer droughts, they can also periodically occur in regions where rainfall distribution is uniform, and in surface soil even though lower horizons are moist (Berkowitz 1988, Richardson 1993, Goncalves *et al.* 1997). This has also been demonstrated in effluent-irrigated forest plantations (EIF) where weed growth is high and the interval between irrigations is too long (Myers *et al.* 1999).

The interrelationship between soil water availability and soil nutrient availability, movement and plant uptake are also very important (Nambiar 1990, Erskine *et al.* 1996, Harper *et al.* 2000, Weston 2001). As the distribution of nutrients is usually concentrated in the topsoil, it is possible for a tree to be under little moisture stress due to access to adequate soil water at depth, but for it to be suffering nutrient

deficiency because the topsoil is dry (Hunter *et al.* 1990). The timing, duration and importance of competition for water and nutrients is therefore interrelated and water x nutrient interactions can occur in many young establishing tree crops (Nambiar 1990, Ludovici and Morris 1998). This can occur even though trees have access to water at depth.

Soil water as a resource has many temporal and spatial characteristics. Its availability is a function of water inputs (rainfall, lateral flow, water table), and outputs (drainage, evaporation, transpiration). This is modified by soil storage capacity (texture, structure and depth) and plant factors (growth habit, life cycle, density and rooting depth). These factors combine to provide dynamic soil water changes over time. At a given site, availability generally increases with increasing soil depth and it is usually uniformly distributed in any given soil layer. The surface soil usually dries out first and the longer the period without rainfall or irrigation the drier the soil gets through both evaporation and plant uptake. Plants with high water-use requirements will increasingly rely on stored soil water if inputs are inadequate or absent. In sandy soils, water storage capacity (field capacity) is low, with the ability to provide water for extended periods limited, compared to finer textured or clay soils. For deep sandy soils, water replenishment relies on rainfall or irrigation, while the influence of a water table depends on its depth and its periodicity.

This chapter describes the magnitude and trends in soil water content and water table fluctuations at the Penna experimental site to determine the importance of competition for water between young *E. globulus* and *H. lanatus*. Changes in soil water content with season, depth, irrigation, weeds and nitrogen application were

investigated. The low annual rainfall (512 mm), high annual evaporation (1300 mm) at this site, in combination with the sandy soil and vigorous grass weeds, were expected to result in reduced availability of water to young *E. globulus* during establishment. The low storage and buffering capacity of the sandy surface soil would be sensitive to changes to water input and output (rainfall and evaporation), drainage and plant use, particularly during the first and second summer after planting. Thus, the effect of grass competition on levels of available water was potentially high. It was hypothesised (1) that water would limit *E. globulus* growth during establishment in the presence of weeds, and (2) that *E. globulus* supplied with I_{High} would grow better in the presence of grass weeds than those supplied with I_{Low} .

5.2 Methods and materials

5.2.1 Irrigation

Irrigation in the I_{Low} treatments had a target annual application including rainfall of around 800 mm yr⁻¹. Irrigation in the I_{High} treatments had a target annual application of 1200 mm yr⁻¹ rainfall. This was approximately 100 mm less than annual pan evaporation at this site and it was anticipated that levels of available water from this latter treatment would not limit growth.

Irrigation was applied initially to the high and low water zones in 8 – 12 mm applications. This was applied between 1800 and 0700 hours to maximise infiltration and minimise evaporation. The irrigation was scheduled for weekly application unless there had been a major rainfall event in the previous week. Rates of application for I_{High} treatments only were increased over the warmer summer months to 20 – 30 mm week⁻¹. All irrigation was stopped during winter each year, except

during the first winter (May–August 1997) when there was a prolonged period of rainfall deficit. When the trees were at least two-years-old (third summer after planting), only I_{High} treatments received irrigation while I_{Low} treatments were rain fed only. This was done to maximise differences between the high and low water treatments, at least in the surface soil, as two-year-old trees were not exhibiting any water stress. This was probably due to tree roots accessing water at depth below the zone of influence of the weeds (1 – 1.5 m below soil surface).

The source of irrigation water was a large excavated channel near the trial site, between the farmland and an area of salt land marsh bordering the Pittwater estuary. This was recharged during winter from sub-surface water from the property catchment area. This water source had been used for irrigating agricultural crops including lucerne and potatoes by the landowner in previous years.

5.2.2 Water table characteristics

Dip wells were installed across the site in August 1997 to monitor water table levels and provide access for sampling water quality. Each well was constructed from 50 mm PVC tube with holes drilled in the lower half, and installed by hand augering (100 mm diam) to 2 m depth, inserting the tube, backfilling with clean gravel (3 mm size) to within 0.7 m of the soil surface, then filling the remainder with 1:3 cement to sand (Figure 5.1).

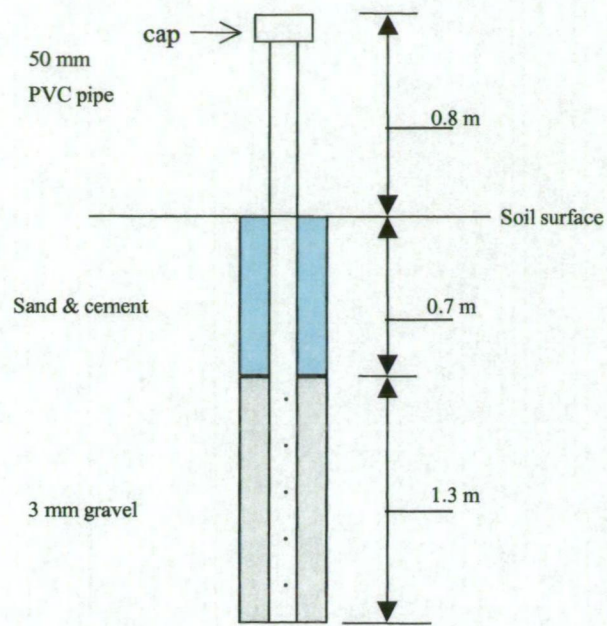


Figure 5.1 Dip well construction

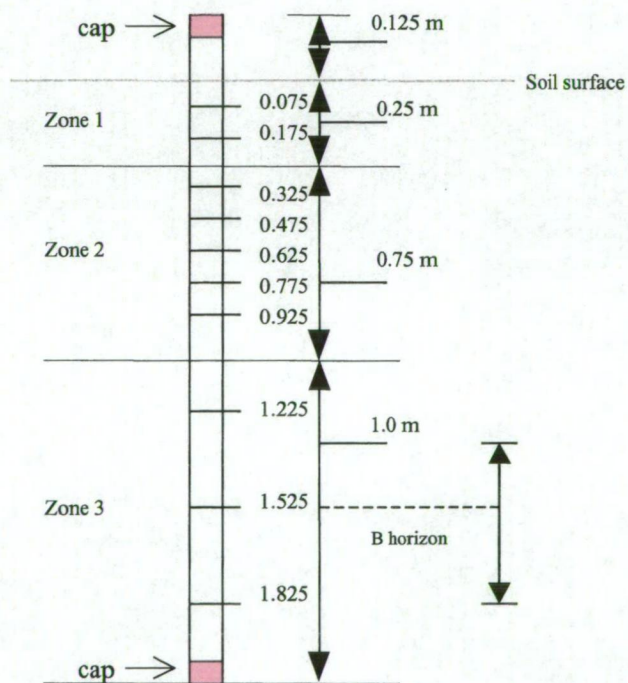


Figure 5.2 Neutron moisture meter access tube installation

Site topography was surveyed to assist interpretation of dip well data and to define soil water status across the site, based on depth to water table and capillary fringe. Readings of water table depth were made from August 1997 to January 1999, at the same time as measurements of soil water content.

5.2.3 Soil water content

Neutron method

Volumetric soil water content (θ) was measured by the neutron moisture meter (NMM) method (Campbell Pacific Nuclear Company (CPN) Model 503 Hydroprobe, Pacheco, CA, USA) in aluminium access tubes (41 mm i.d.). Tubes were located in three replicates of eight treatments across the site in Experiment 1. Each tube was positioned in the centre of four trees within the internal 12-tree measurement plot and installed to depths of 2.0 m by hand augering ahead of the driven tube. These depths extended through the sandy A horizon into the clay B horizon (Figure 5.2).

Measurements in the first year were generally taken every two weeks during the spring, summer and autumn (October – April), and up to four weekly during winter (May – September). Counts were made at 11 levels (depths) in all deep access tubes at 0.15 m intervals down to 1.0 m and at intervals of 0.3 m below 1.0 m (Figure 5.2). The same plot measurement sequence was maintained throughout. NMM readings were normally done two – three days after application of irrigation (Figure 5.3).

Neutron probe calibration

Calibration of the neutron probe was done during wet (May 1999) and dry times (February and May 1997) at the field site across a range of soil water contents. The relationship between neutron count ratio and volumetric moisture content was established (Greacen *et al.* 1981). Two separate calibrations were necessary to determine the volume fraction of total water for both surface and sub-surface zones (sand horizons). Soil of existing and newly installed access tubes was sampled to compare the measured count rate ratio (CRR) in the access tube with the volumetric water content (θ) of the samples. Samples were collected from a range of depths down to 0.6 m. At each selected depth, three soil samples were obtained, stored at 4°C and then analysed for θ and bulk density after drying at 105°C for 48 h. The soil profile was considered as three main zones (1,2,3). Zone 1 relates to the Ap surface horizon (0-25 cm) where plant roots were most concentrated. Zone 2 relates to the sandy A2 horizon (25 – 100 cm). Zone 3 is below 100 cm (Figure 5.2). As changes in soil water content were not analysed below 100 cm due to the over riding influence of the water table in this zone, the calibration for this depth is not presented.

CRR was regressed on θ and inverted to provide Equations 5.1 and 5.2 for soil zones 1 and 2, respectively, to 1.0 m depth. W (Weedy) treatments had a stronger regression ($r^2 = 0.92$) than WF (Weed-free) ($r^2 = 0.83$) but these were not significantly different, therefore data were combined at this level. There was no significant difference in soil bulk density within each zone.

Zone 1 (0 – 25 cm) Ap horizon

$$\theta = (\text{CRR} - 0.03) / 1.589; r^2 = 0.876; n = 36 \quad (5.1)$$

Zone 2 (25 – 100 cm) A2 horizon

$$\theta = (\text{CRR} - 0.029) / 2.298; r^2 = 0.996; n = 4 \quad (5.2)$$

where:

θ = volumetric soil moisture content ($\text{cm}^3 \text{ cm}^{-3}$)

CRR = count rate ratio of detected neutrons within the hydroprobe shield

Total water content of each zone W (mm) was calculated from the volume fraction of water (θ_i) at each measurement depth integrated over the depth of each zone (Z_i , mm) (Equation 5.3). Thus:

$$W = \sum \theta_i Z_i \quad (5.3)$$

Individual depths down to 1 m were also evaluated.

As part of the regular soil sampling for nutrient analysis (NH_4^+ , NO_3^- and PO_4^-), soil gravimetric water content (%) was determined for the 0 – 10 cm soil depth. This was converted to volumetric water content (θ) (Equation 5.4) as:

$$\theta = (\text{gravimetric water \%}) / 100 \times \text{bulk density} \quad (5.4)$$



Figure 5.3 Neutron Moisture Meter on trolley. Cans cover neutron access tubes which were part of a shallow transect series (data not presented).

5.2.4 Field capacity and plant available water

Soil field capacity (W_f) was determined for one access tube in each replicate from measurements taken during May 1999 (tree age 2.5 years). A metal ring (40 cm wide) was placed around each access tube and 40 L of water added over a 2 h period (equivalent to ~ 320 mm rainfall). There had been < 2 mm rainfall over the previous 27 days and adjacent dip wells were dry, while 16 mm rainfall occurred during the day of water application. Neutron readings of the tube were taken prior to, then 4, 26 and 72 h after water application. Field capacity was taken as the soil water content after 48 h drainage (Cassel and Nielsen 1986).

Plant available water (W_a) was defined as the difference between field capacity and permanent wilting point for the soil. This is an approximate value but allows useful treatment comparisons to be made. Pre-watering soil water content was as low as 2.3

% in the three plots and this was assumed to be the permanent wilting point (W_o).

Plant available water for each zone was calculated from (Equation 5.5).

$$W_a = \text{zone depth (mm)} \times 1 \times P_b \times (W_f - W_o) \quad (5.5)$$

Where: zone depth = 250 mm for Zone 1 and 750 mm for Zone 2, P_b = bulk density,

W_f = field capacity for zone, W_o = permanent wilting point for zone

An alternative method for calibration of soil samples would have been to use a pressure plate to develop a soil – moisture characteristic curve. This would have allowed the calculation of soil matric potential values for soil water and may have provided more interesting correlations with plant moisture stress.

5.2.5 Data analysis

Volumetric soil water content (θ) and plant available water (W_a) were calculated for each access tube for each of the measurement depths (0 – 25 cm and 25 – 100 cm) and each measurement date. Each tube was defined by the treatment in which it occurred. The GENSTAT ANOVA procedure (Genstat 5 Committee 1994) was used to test for differences between treatments for each zone at each measurement date. A split plot design was used that included an interaction between treatments. Irrigation level was used as the main plot and weed and nitrogen treatments as sub-plots.

Where soil water content was significantly different ($p < 0.05$), LSD's were used to make multiple comparisons of treatment means.

A modification of Zone 1 was analysed. The top 10 cm was excluded (effectively leaving 10 – 25 cm depth) as this provided a more sensitive analysis of the treatments. The surface 0 – 10 cm depth had very low θ . This was possibly linked to neutron leakage and compaction of the zone over time, reducing the measurement depth.

5.3 Results

5.3.1 Soil physical characteristics

The duplex soil profile of sandy A horizon over clay B horizon had an overriding influence on the soil and plant water relations at the site. Texture of the A horizon is classified as a loamy sand, with depth to the clay B horizon varying from 1.2 m to > 2 m across the site. The bulk density of the sand ranged from 1.35 g cm^{-3} in the surface 25 cm (Zone 1) to 1.5 g cm^{-3} at 50 cm depth (Zone 2). This was consistent across the site.

5.3.2 Climate

Rainfall and evaporation details are provided in Chapter 2, Section 2.2.4, page 15.

5.3.3 Irrigation

Irrigation was applied during three main periods that were associated with each growing season (Figure 5.4). The bulk was applied for six to eight months each year during spring, summer and autumn, and little or none during winter. The difference between evaporation, rainfall and irrigation is indicated in Figure 5.4 along with the variable rainfall distribution and irrigation applied in I_{Low} and I_{High} . For the first seven weeks after planting, irrigation (I_{High} and I_{Low}) was approximately 20 mm

week⁻¹ (split into two applications). Subsequently, I_{Low} received 9 mm week⁻¹ and I_{High} , on average, 22 mm week⁻¹ (range 13 to 39 mm). In this first growing season, no further irrigation was applied to I_{Low} after late April, 1997. In I_{High} , irrigation was applied until late June (Table 5.1) because of a dry winter.

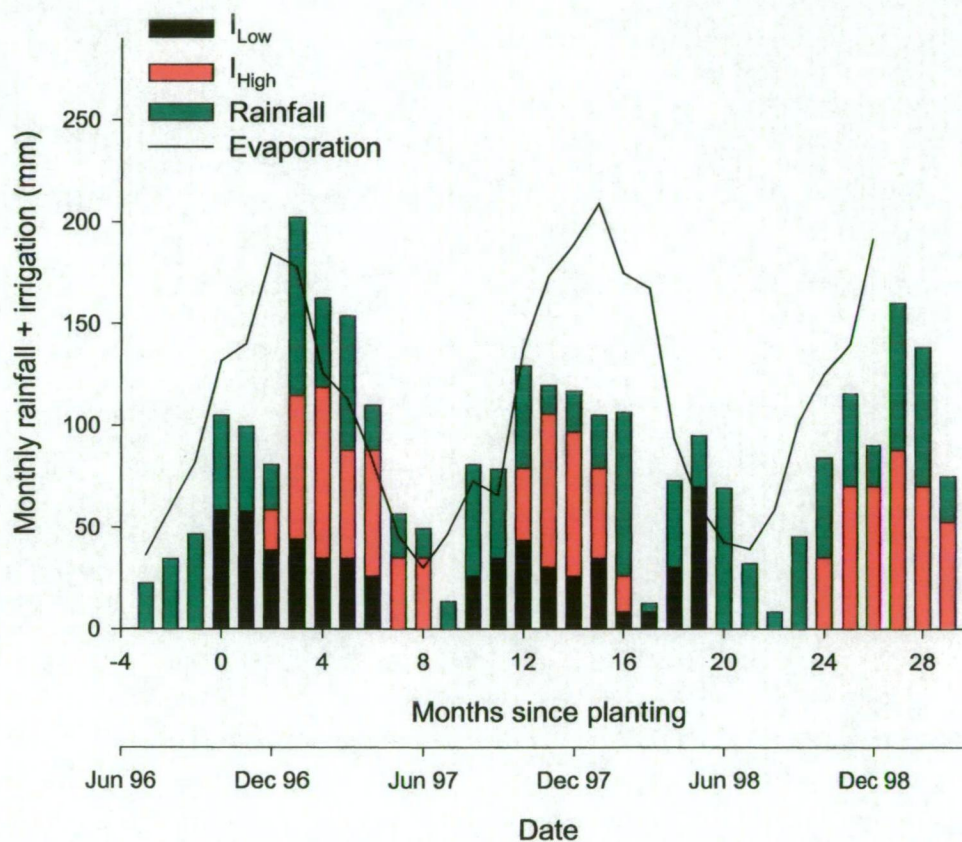


Figure 5.4 Rainfall, irrigation (I_{Low} and I_{High}) and evaporation. The total water input for the I_{Low} treatment includes the black and the green bars in each period. Water inputs for the I_{High} treatment include all three bars together for each period (cumulative value for black, red and green). The data is presented this way to illustrate the water inputs for the two irrigation treatments, plus rainfall, compared to the pan evaporation over the study period.

Irrigation recommenced in both treatments in August 1997, each receiving 9 mm week⁻¹ in one application. From mid October I_{High} received 18 mm week⁻¹ in two applications, from November to mid December 26 mm week⁻¹, and then 18 mm week⁻¹ until mid February 1998. Concerns regarding increasing water salinity led to occasional watering only between March to May 1998 in I_{High} and I_{Low} treatments.

In the third main period of irrigation between October 1998 to March 1999, I_{High} received 18 mm week⁻¹. I_{Low} received no irrigation. The main purpose was to provide water for grass growth as tree responses to irrigation were not present and it was expected that all trees had access to water at depth.

Table 5.1 Irrigation for each year along with periods of application

Year	Rainfall (mm)	I_{Low} + rainfall (mm)	I_{High} + rainfall (mm)
(a) July 1996 – June 1997	468	765	1121
July 1997 – June 1998	441	757	991
July 1998 – June 1999	454	454	841
(b) Oct 1996 – Sep 1997	475	834	1181
Oct 1997 – Sep 1998	415	670	912

Summing water inputs (irrigation plus rainfed) from winter to winter indicates that I_{Low} received approximately 760 mm year⁻¹ during the first two years of growth (Table 5.1a). This was around 95% of the target rate. I_{High} received 93% of the target rate (1200 mm) in the first year, then due to poor water quality, was reduced to 83 % and 70 %, respectively, of the target during the second and third year.

On a tree age basis (Year 1: October 1996 – September 1997; Year 2: October 1997 – September 1998), I_{Low} received the target rate during the first year, and 84% of the target during the second year. For I_{High} the target rate was also achieved during the first year, but was 76% of the target in the second year (Table 5.1b).

5.3.4 Water table

The depth to water table and changes in height with respect to surface topography is shown in Figure 5.5a,b. Based on depth to the slowly permeable clayey B horizon, three categories of site water status were identified: high (< 1 m), medium (1 – 1.5 m) and low (>1.5 m). Low water status was equated with a deep sandy horizon, particularly in Block 3. Most of the dip wells indicated a relatively stable water table but several fluctuated widely. The shallow group (dip wells 2, 3, 4, 5, 10) occurred in the lower part of the site. The medium group occurred on the mid slope position of the site (dip wells 1, 6, 8) while the deep group occurred at the highest parts of the site (dip wells 7 and 9 in Block 3).

Figure 5.6 shows seasonal trends in the water table across the site as mean depth over all dip wells in each group. There appeared to be summer decreases and spring increases with a general downward trend over time. Water table levels were lowest at the end of summer in autumn. In winter, at age 10 months (August 1997), the shallow water table depth was between 60 – 100 cm below the soil surface. This increased to 115 cm in autumn. In winter 1998 it had risen to 40 – 65 cm but then declined to 140 – 165 cm in January 1999. Dip well 3 and 10 fluctuated widely from dry to very wet on a number of occasions (individual data not presented).

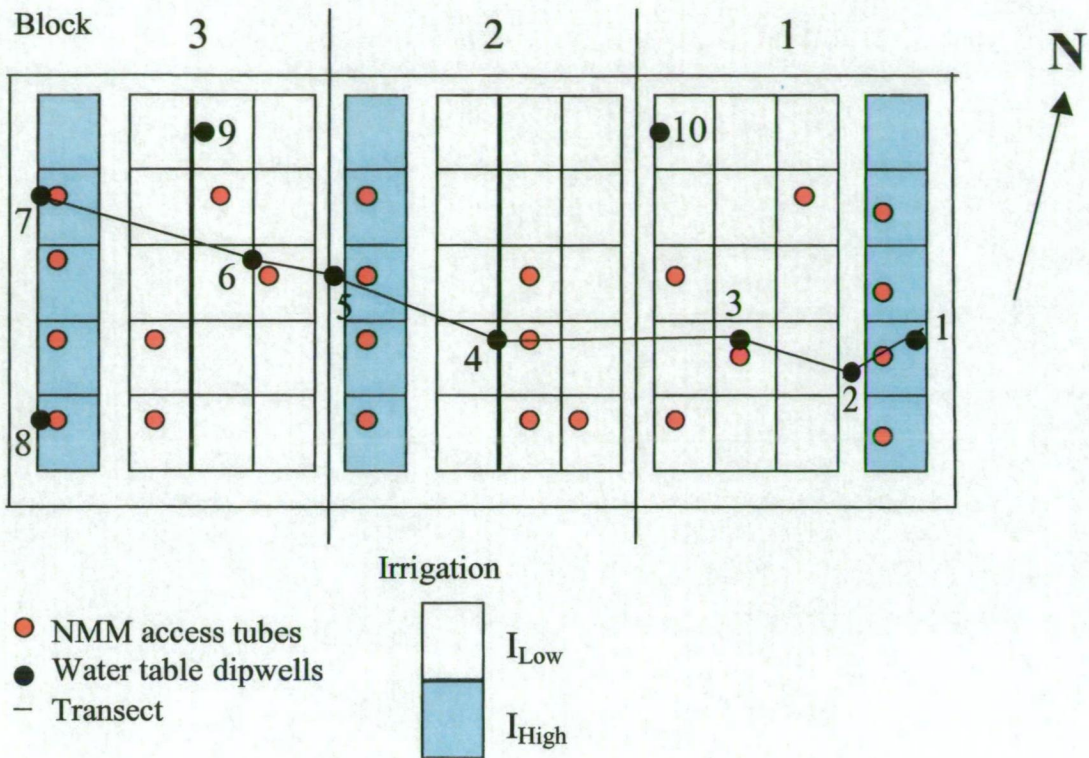


Figure 5.5a Location of neutron access tubes and dipwells across the site.

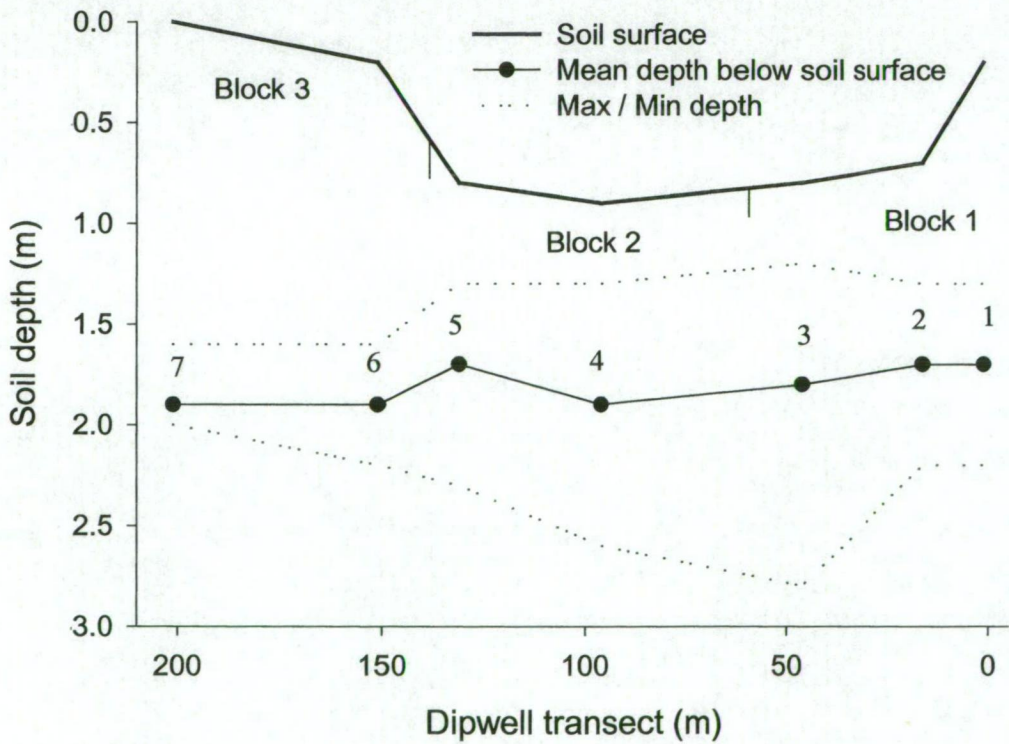


Figure 5.5b Soil water table trends in relation to surface topography across the site.

In those parts of the site with medium water status, the water table was between 150 – 175 cm below the soil surface in winter and had decreased to 170 – 180 cm by autumn 1998. This increased back to between 115 - 130 cm in winter 1998. This was followed by a general decrease to Jan 1999 where depths ranged from 180 cm to dry. The deep water group was generally dry to 2 m with free water on three occasions only (October 1997, February 1998 and June/July 1998) (Figure 5.6).

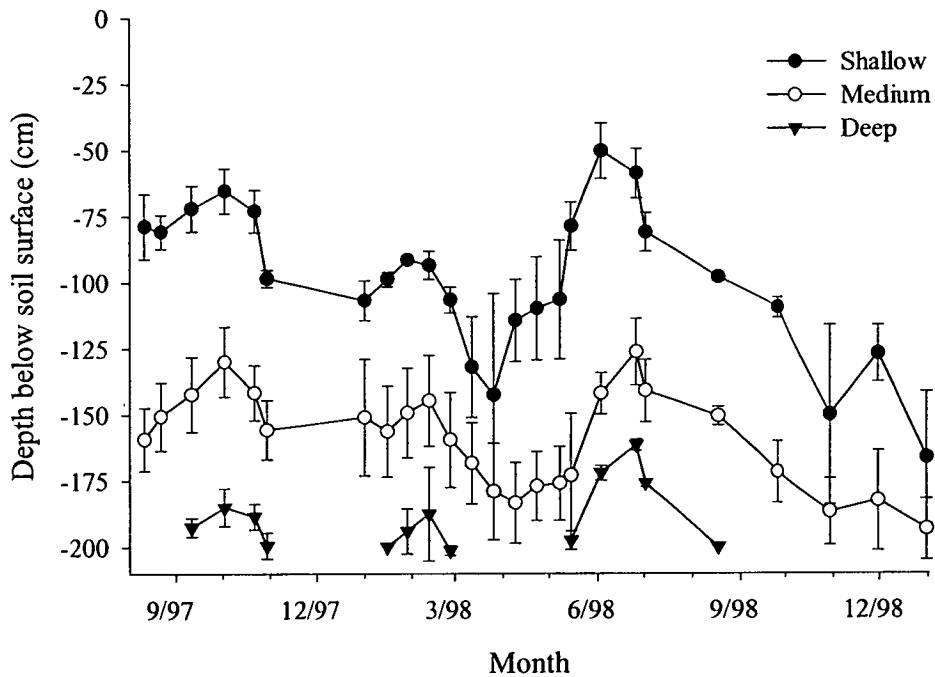


Figure 5.6 Groundwater trends for the three groups – shallow, medium and deep during the period August 1997 – January 1999 (age 10 – 27 months). Error bars are standard errors of the means.

Above the water table was a zone of water upflow. This is referred to as the capillary fringe and occurs in response to tension and capillary rise in the soil above the water table. At this site it was observed to occur up to 50 cm above the water table. This capillary fringe played a significant role in extending and maintaining high soil water content to this depth above the water table across most of the site.

5.3.5 Soil water content by zone

Soil water content (θ) during the two years of measurement was influenced by season and year, and irrigation, nitrogen and weed treatment. Grass presence (W) generally lowered θ in the surface soil compared to WF during the first year with more equivalence between the treatments during the second year (Figure 5.7a). On average, θ was 8% lower in W than WF during the first year with treatment differences during the second year much smaller. Both treatments followed the same trends in both years. In the subsoil (25 – 100 cm) θ was five to six times higher than in the surface soil (Figure 5.7b). Water availability followed similar trends to the surface soil but there was much less variation. θ in W treatments were 15% lower than in WF treatments during the first year ($p < 0.05$) and 5% lower in the second year ($p > 0.05$) (Figure 5.7b). Therefore, the major impact of weeds in both the surface and sub surface soil water occurred up to the second summer (Jan 1998) (tree age 15 months) after planting.

Block 3 was consistently drier than the other two blocks, due to a deeper A horizon and a deeper water table and associated capillary fringe. Block 2, situated in the lowest part of the site, was consistently the wettest of the three blocks with no significant evidence of lower θ under weeds. This is in contrast to plots in Block 3,

particularly those receiving N_{High} . In this Block θ was 31 – 45 % lower in the W than WF treatment during the first summer and 50 – 53% lower in the second spring (October- November 1997). In the second year W had similar θ to WF treatments (data not shown).

Analysing the 10 – 25 cm depth in Zone 1, allowed improved definition of treatments. All treatments showed similar trends in the surface zone (10 - 25 cm) throughout the study (Figure 5.8a,b). WF had generally higher θ than W treatments, particularly during the first year. However, differences between treatments in the second year were less clear and there was much higher fluctuation compared to the first year.

At most measurement times throughout the study there were significant third order interactions (water x nitrogen x weed control) along with significant effects of weeds. θ was significantly lower under weedy than weed-free conditions for the first year of growth, however, in the second year, θ was similar to or greater than in weed-free treatments. Surface soil in unfertilised weedy plots receiving I_{Low} , was drier than in WF plots for the entire two-year period, while soil under N_{High} W plots, was drier for only the first year, before becoming wetter than in WF plots during the second year.

Soil receiving I_{High} , was drier under weedy than weed-free conditions, until tree age 8 months (winter 1997) before becoming wetter than in weed-free plots for the remainder of the study. Where fertiliser was applied in conjunction with I_{High} , weedy plots were drier than weed-free plots for the whole period.

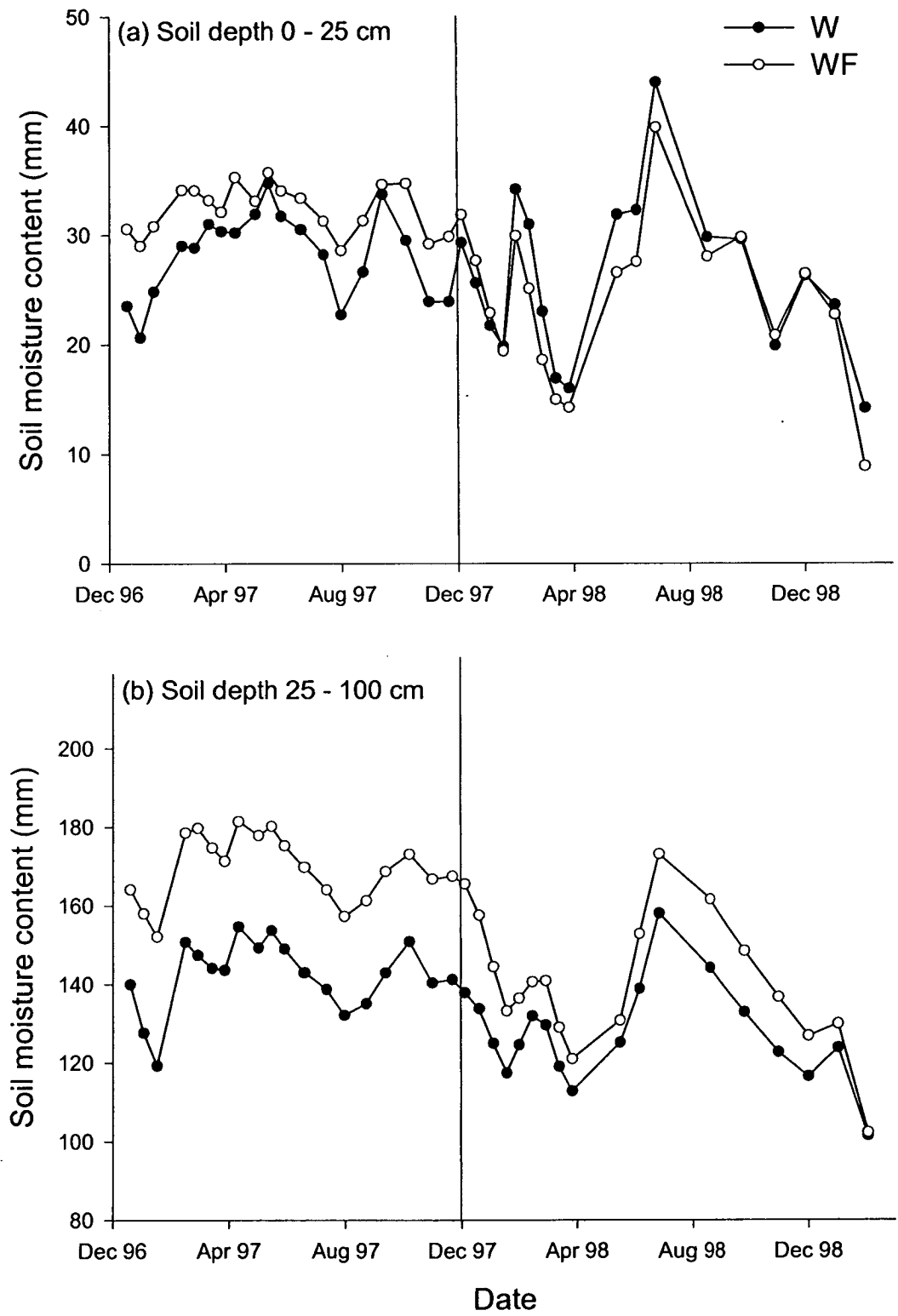


Figure 5.7 ab Effect of weeds on soil water content θ (mm) in zone 1 and 2 over years 1 and 2.

Gravimetric measurements in the 0 – 10 cm zone showed very low θ (5.4 mm in winter and 2.7 mm in summer). These were consistent with NMM measurements for the same depth. The timing and frequency of the gravimetric measurements showed the same general trends as the NMM but missed much of the short-term variation. Seasonal effects were present, with θ increasing in late autumn, winter and early spring, followed by a decrease over summer and early autumn. The least amount of soil water occurred during March at the end of summer (data not shown).

The effect of nitrogen fertiliser applied to grass was reflected in the water x nitrogen x weeds interaction. In Block 2, θ under grass receiving I_{Low} and N_{High} , was higher than grass receiving N_{Zero} . There was no major difference in θ for plots receiving I_{High} . There was also no evidence of drier soil during spring under fertilised grass compared to unfertilised grass at any depth down to 50 cm. However, such an effect was evident in Block 3, with lower θ under N-fertilised grass.

While much of the variation in θ could be related to seasonal factors and water inputs (rainfall and irrigation), some fluctuations, especially during the second year, could not. A large peak in θ occurred during July – August 1998 in both surface and sub surface soil layers (Ap and A2) (Figure 5.7ab), which was also matched by an increase in the water table (Figure 5.6). This event occurred when water inputs from irrigation and rainfall were low. The relationship between θ and total water inputs (mm month^{-1}) during the two years was determined to be weak for the surface and sub surface soil, at both levels of weed treatment (Figure 5.9). This indicates that water inputs from outside the study plots influenced soil water relations.

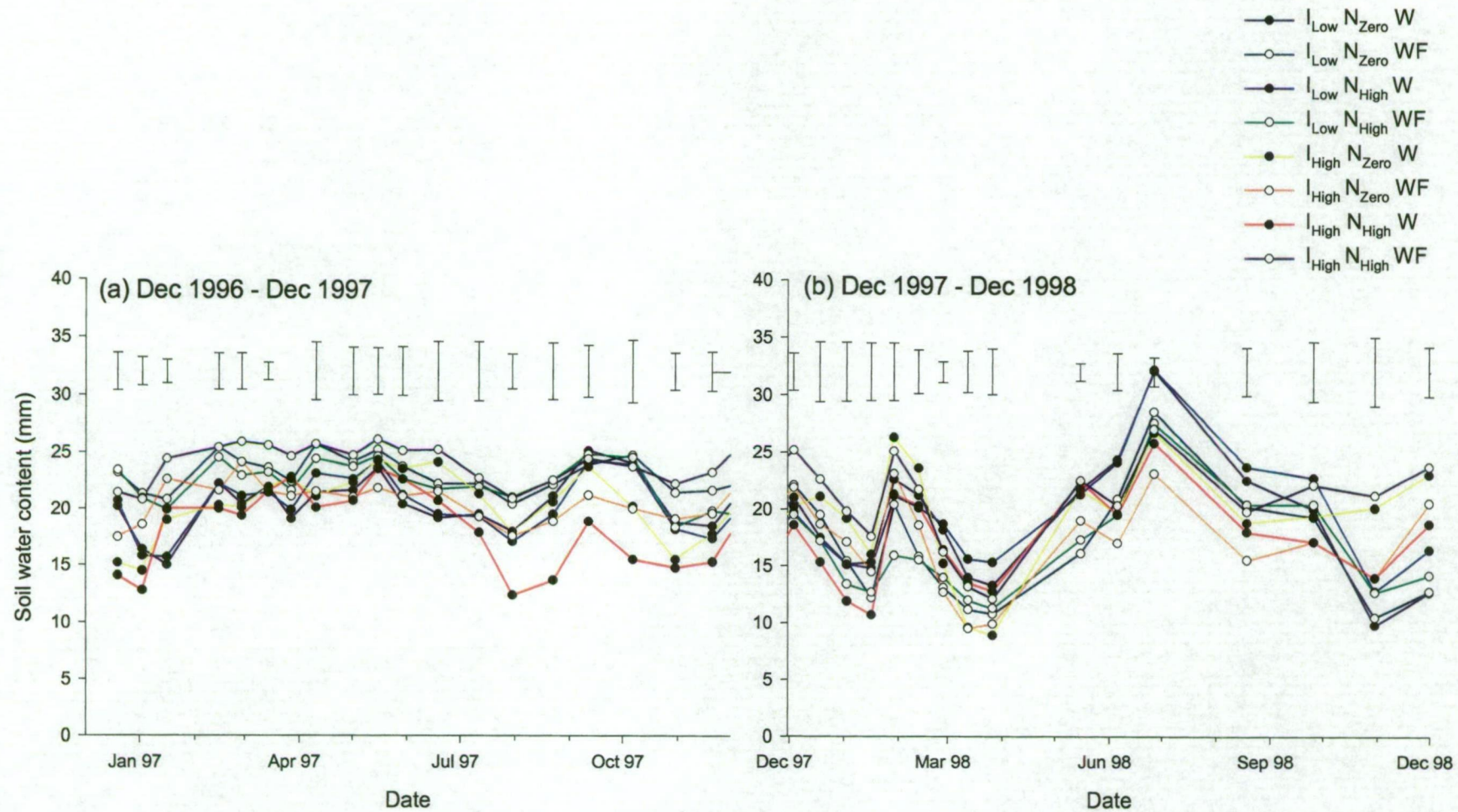


Figure 5.8 Surface soil water content θ (mm) (10 – 25 cm) during (a) first and (b) second year of growth. Error bars are LSD's (p=0.05)

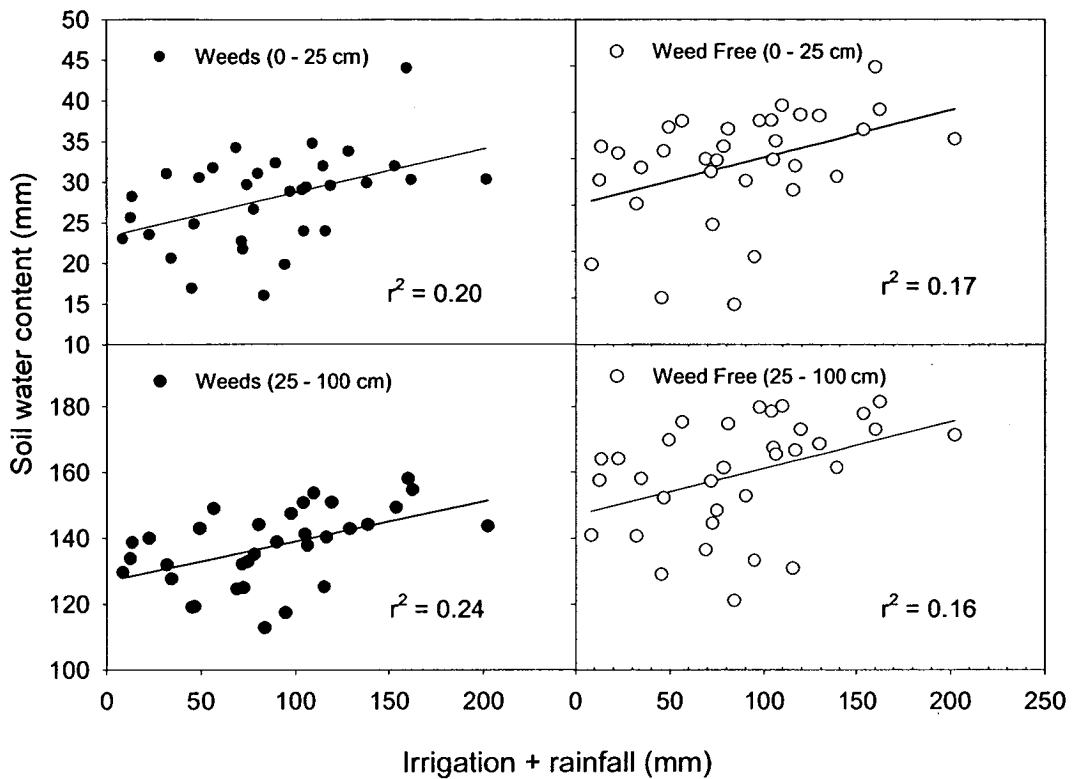


Figure 5.9 Relationship between soil water content (θ) and total water inputs (rainfall and irrigation, mm month^{-1}) for surface (0 – 25 cm) and sub surface (25 – 100 cm) soil layers under weeds and weed-free.

5.3.6 Soil water content by individual soil depths

Weed treatments plotted in relation to soil layers (Figure 5.10) shows the same trends in θ as previously described for zones. There was more water at depth and also less fluctuation than in the surface layers, for example as shown in relation to the large peak in July 1998. The differences between W and WF were greater with depth. The 25 – 40 cm zone had the lowest θ throughout the two-year period. There was greatest variation and fluctuation in the surface soil of plots in Block 3 where weeds reduced θ by up to 50% during the first year (Figure 5.11). In contrast to the other two blocks, the surface soil had higher θ than sub surface layers (down to

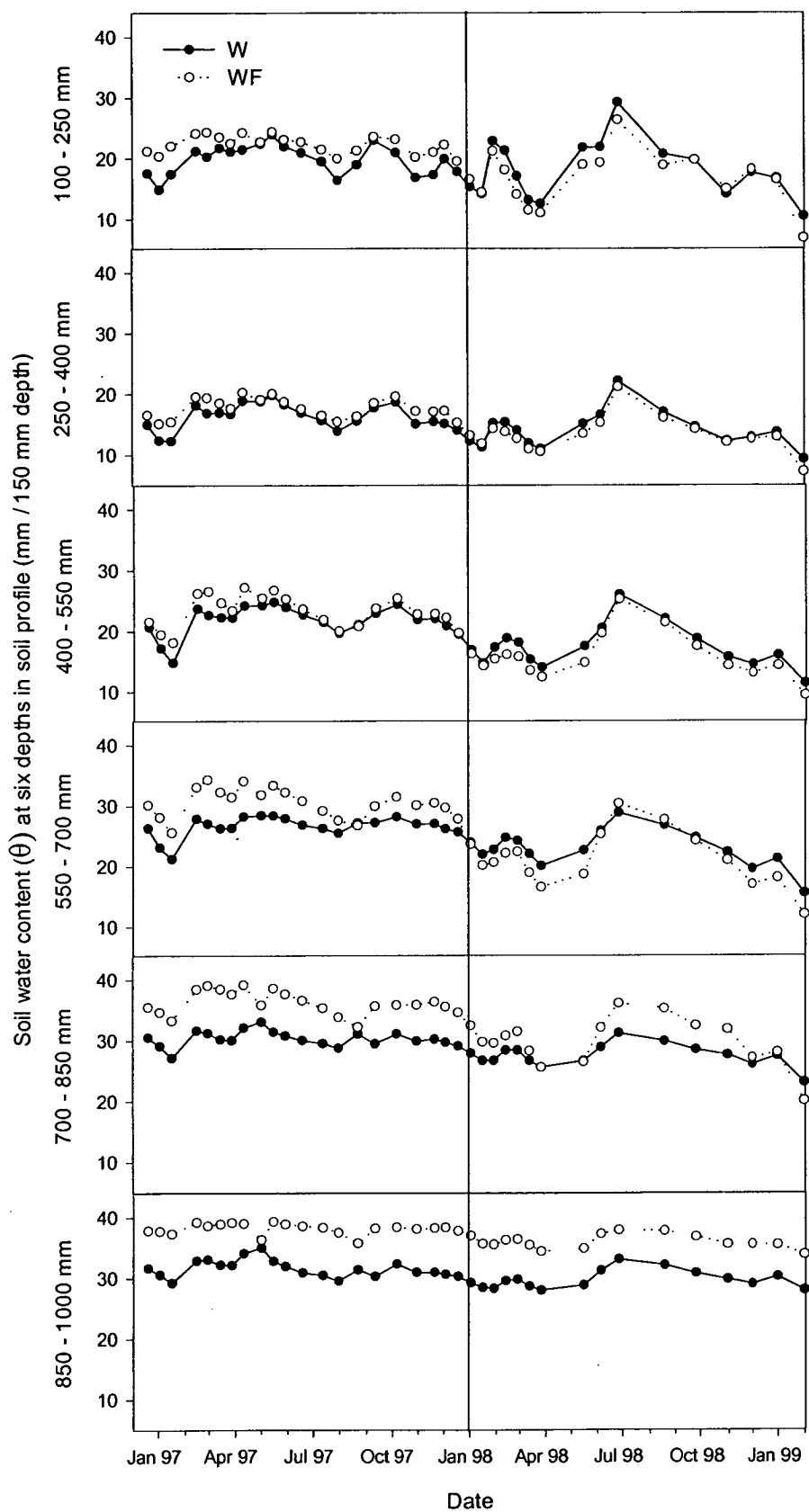


Figure 5.10 Soil water content θ at six depths over two years

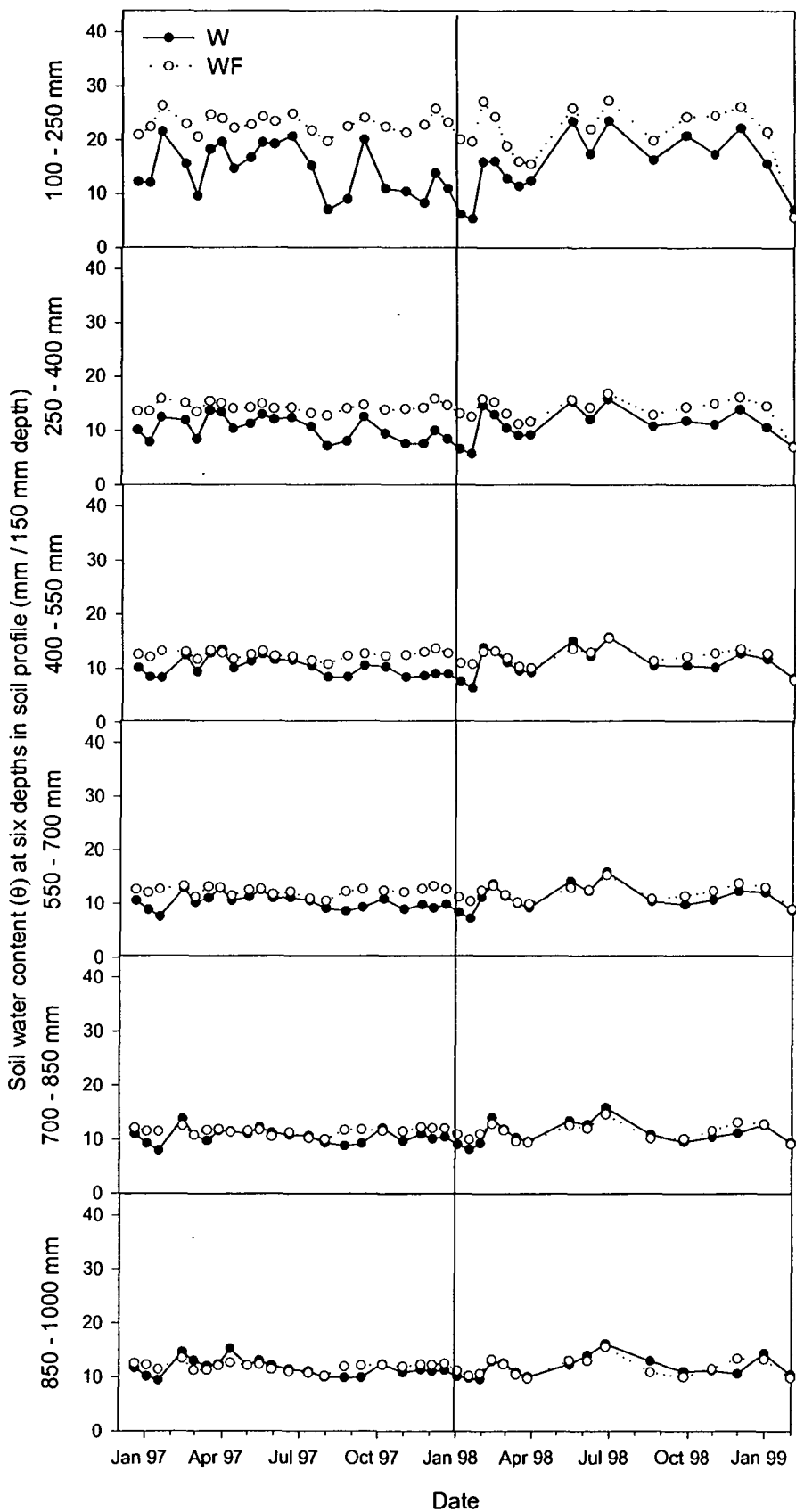


Figure 5.11 Soil water content at six depths over two years for two plots in Block 3 ($I_{\text{High}} N_{\text{High}} W$ and $I_{\text{High}} N_{\text{High}} WF$)

100 cm) for most of the year (Figure 5.11), reflecting the lower influence of the water table in this block. In this Block θ was similar between treatments, at 70 – 85 cm depth.

5.3.7 Field Capacity and Plant Available Water

Field capacity (W_f)

The soil was very dry prior to measurement of W_f in May 1999. There had been no rain or irrigation for 27 days previously. Following the application of water, wetting fronts for 4, 26 and 72 h post application showed parallel decreases in θ by depth over time (Figure 5.12a,b,c). The exception was plot 30, which had an initial increase of θ in the top 50 cm before smoothing out down the profile. It was also evident that θ at 75 cm did not increase following application of water, indicating saturated conditions at this depth and the strong influence of the water table. This was also evident in plot 10, while in plot 45 (Block 3) water drained to the bottom of the 2 m profile.

Mean W_f for the top 1 m depth was derived from the three WF plots sampled (Figure 5.13). Values for depth 0.775 and 0.925 m were based on plot 45 only as the other two plots were strongly influenced by the water table and the associated capillary fringe at these depths. The mean θ by depth (per 100 mm) was 11.7 mm, equating to 117 mm storage capacity for 1 m depth (A_p and A₂ horizon). W_f increased with depth, probably reflecting increasing clay content in the soil and much lower water content of the surface soil (0 – 100 mm).

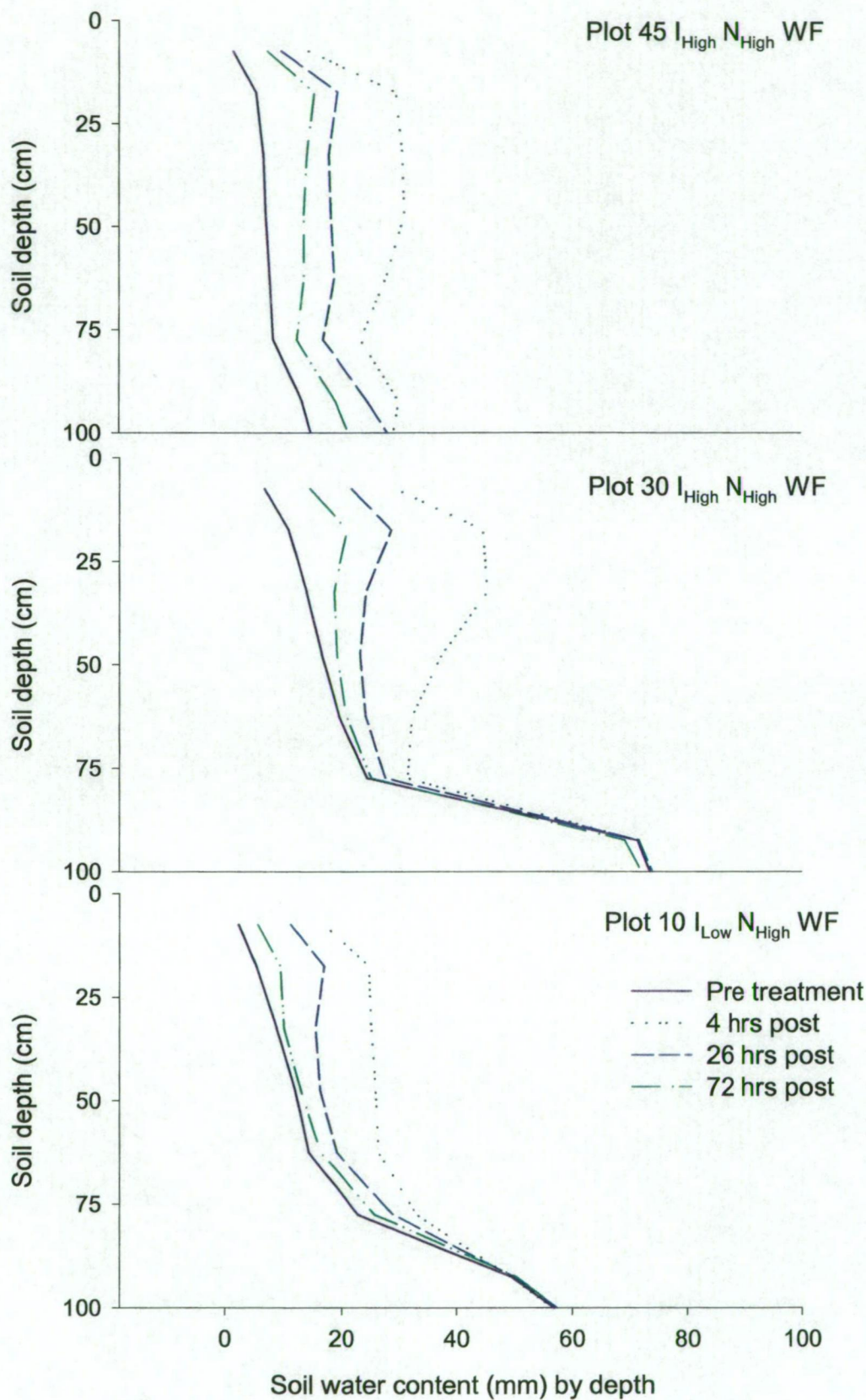


Figure 5.12 Soil field capacity measurements on three plots

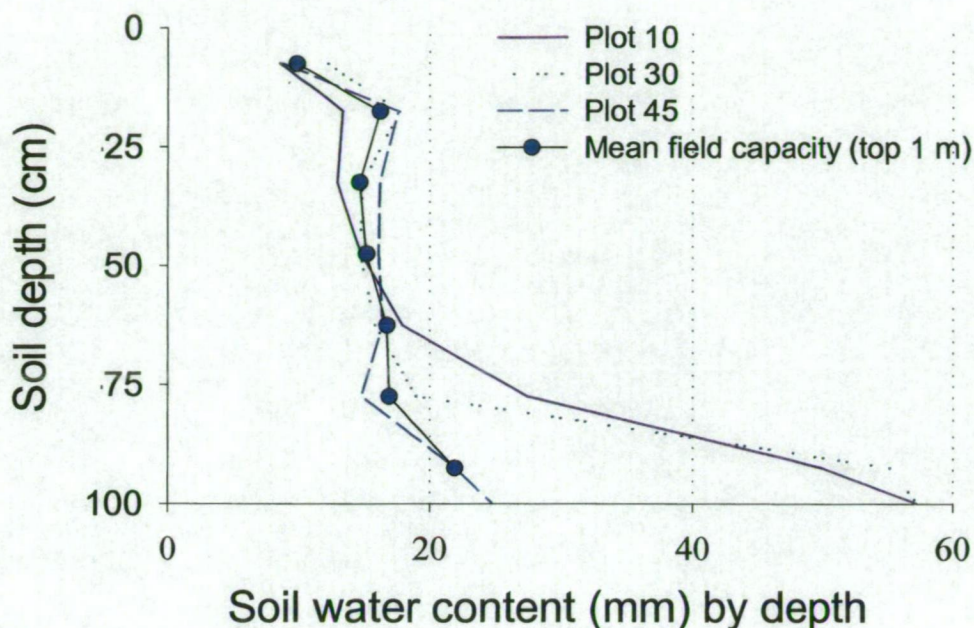


Figure 5.13 Soil field capacity 48 hours post watering on three plots

Plant available water (W_a)

The mean soil water storage in the top 1 m of soil, across the site, at field capacity was calculated as 117 mm. Based on the soil moisture content of the dry soil prior to watering; the soil moisture content at wilting point was derived and was 23 mm.

Therefore, plant available water (W_a) was approximately 95 mm in the top 1 m. W_a was lowest in the 0 – 25 cm zone and this occurred during March 1998 (tree age 18 months), when $< 50\%$ W_a was available across all treatments. Before March 1998, W_a in WF treatments was consistently above field capacity but in W treatments was more variable. In May 1998 (tree age 20 months) most treatments had regained full W_a . From age two years (October 1998), all I_{Low} treatments were below field capacity, coinciding with no further inputs of irrigation to these treatments from this time.

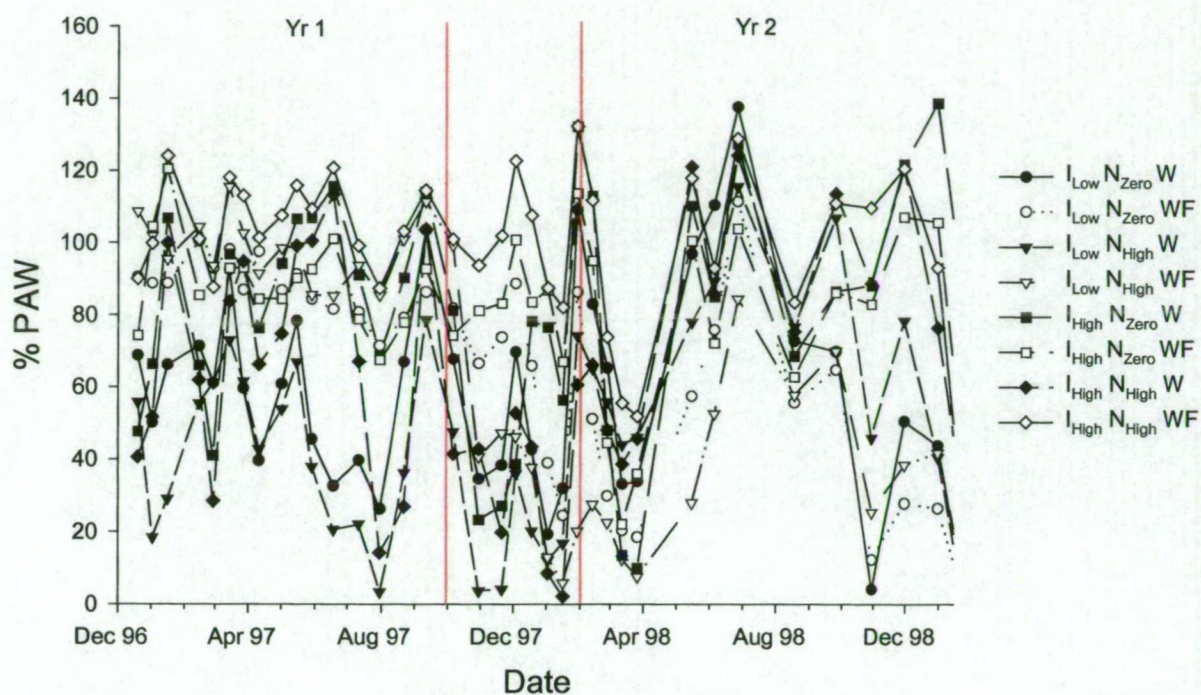


Figure 5.14 Plant available water in surface soil (0 – 25 cm) in Block 3 for years 1 and 2.

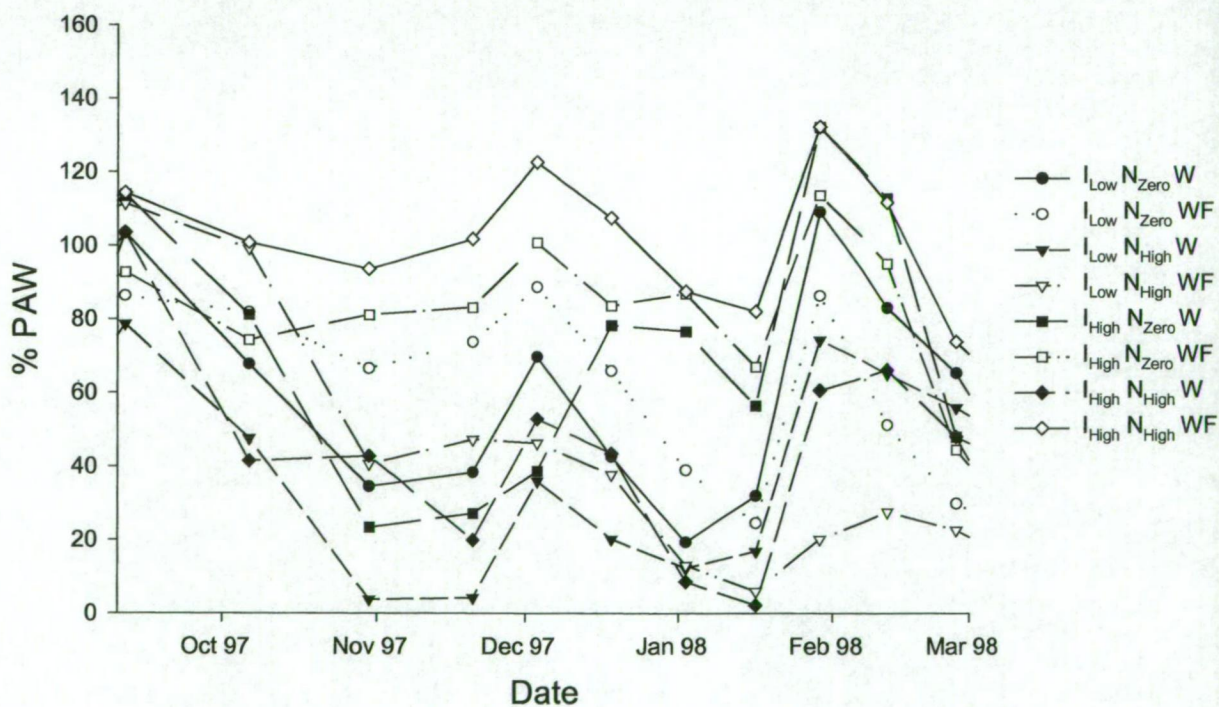


Figure 5.15 Plant available water in Block 3 (0 – 25 cm) from October 1997 to March 1998 (enlarged red section of Figure 5.14) highlighting the nitrogen and weed effect in this block.

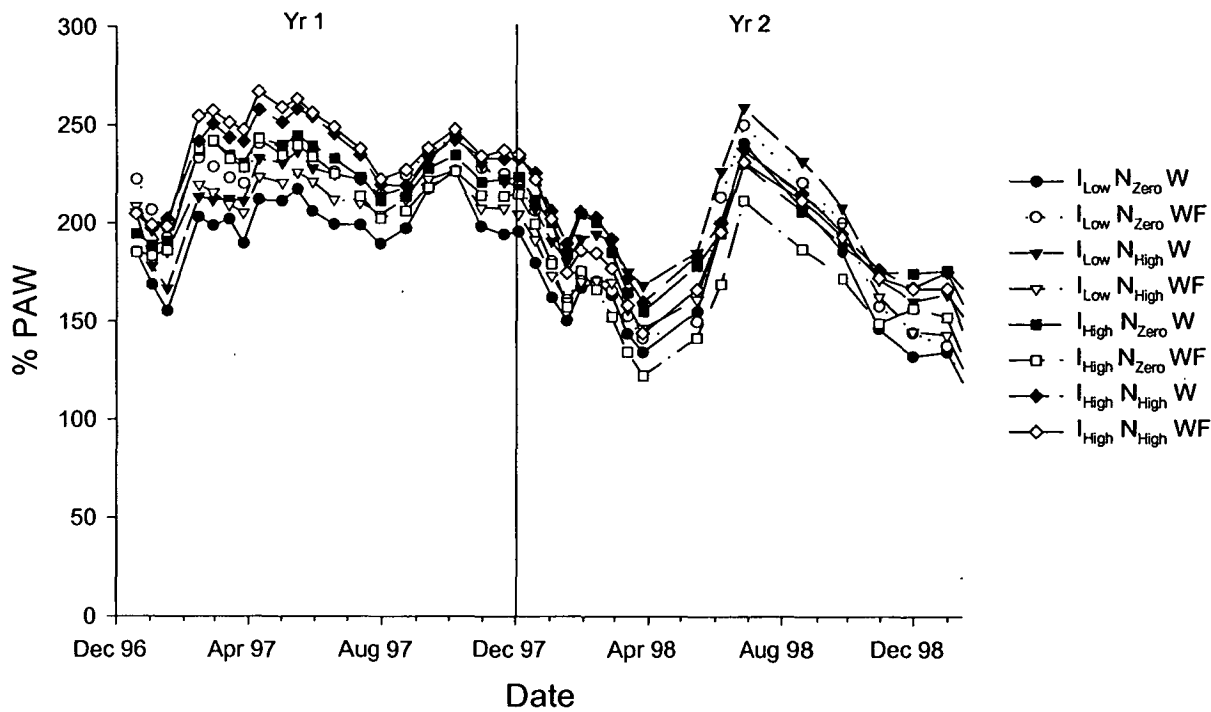


Figure 5.16 Plant available water in Block 2 (0 – 100 cm) for years 1 and 2.

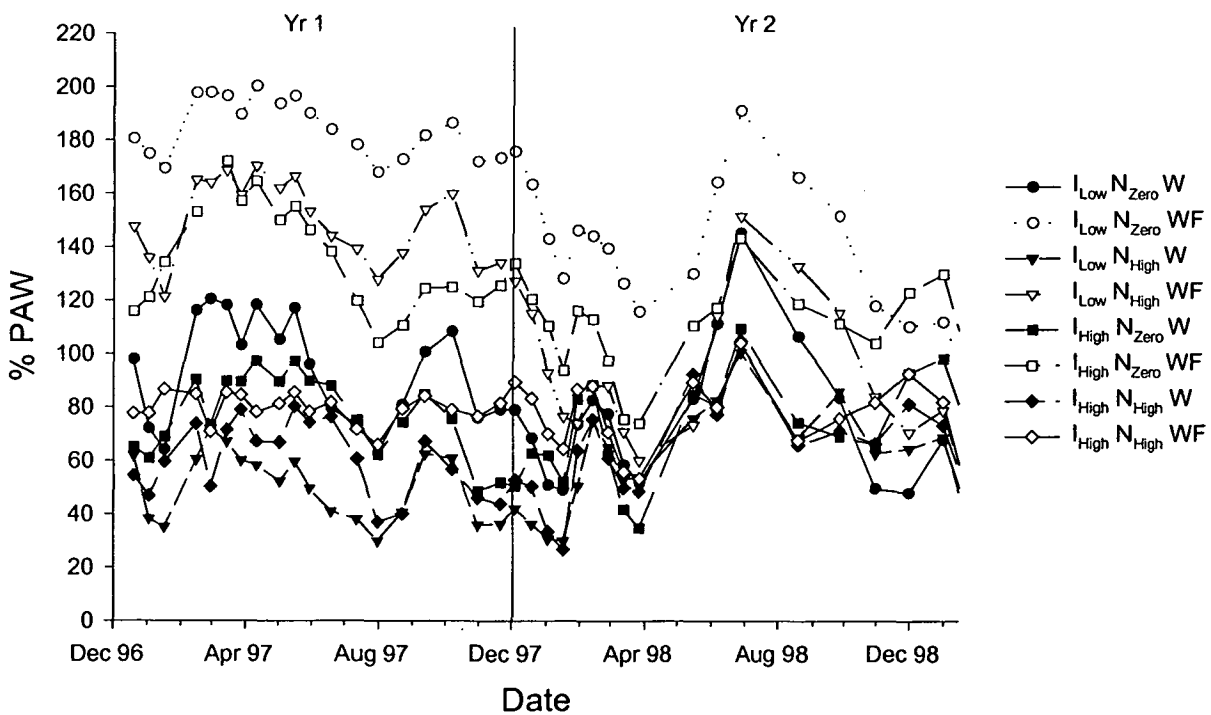


Figure 5.17 Plant available water in Block 3 (0 – 100 cm) for years 1 and 2

Block 2 with the shallowest water table had θ well above field capacity for most of the period. Block 3 treatments showed much more variation, with six periods of low water availability (Figure 5.14). As for Blocks 1 and 2, during the first year, W treatments had lower θ than WF treatments, while in the second year the differences were more variable. I_{Low} WF had $> 70\%$ W_a until January 1998 (age 15 months), while I_{High} WF was generally higher and did not drop below 70% W_a until one month later (February 1998). I_{Low} W treatments had much lower soil water content with greater fluctuation throughout the year and were as low as $20 - 40\%$ W_a in June – July 1997 (age 8 – 10 months). The effect of nitrogen application was also shown in this period where N_{High} W had very low W_a (4% W_a) in October – November 1997 compared to N_{Zero} W ($35 - 38\%$ W_a). This was also evident in the I_{High} W treatments but not to the same extent. In January 1998 all W treatments had low W_a with N_{High} the lowest. At this time I_{Low} N_{High} WF was also low. Figure 5.15 shows an expanded section of data on plant available water changes (as in Figure 5.14) from September 1997 to March 1998 to highlight the effects of nitrogen and weeds.

In Block 2, mean W_a in zone 1 plus zone 2 ($0 - 100$ cm) was up to 2.5 times higher than field capacity for most treatments (Figure 5.16), reflecting the influence of the water table. The variation between treatments in Block 2 was small compared with Block 3 (Figure 5.17) where all WF treatments were greater than 100% W_a except I_{High} N_{High} WF which was $70 - 80\%$ W_a . All W treatments were $< 100\%$ W_a , especially N_{High} W which was frequently below 50% W_a . On average W treatments had less than half the available water contained in WF treatments.

5.4 Discussion

The overriding influence on soil water availability at this site was the shallow water table, which along with the capillary fringe, provided high levels of available water that were readily accessible for plant use in most plots and treatments during most of the two-year study. Consequently, weeds had a low impact on levels of available water except in the surface soil and only after long dry periods. In addition, irrigation treatments applied to simulate two levels of rainfall input and hence soil water availability were compromised. I_{High} did not significantly improve tree or weed growth. However, the influence of both weeds and irrigation varied across the site due to varying depth to the water table. In Blocks 1 and 2, the water table was <1.5 m deep, and θ (0 – 25 and 25 – 100 cm) was at or above field capacity for much of the study period. In Block 3, the water table was deeper (>2 m), and therefore rainfall and irrigation inputs, plant water use and drainage were more important factors affecting θ .

Block 3 therefore provided the strongest evidence of the impact of weeds on θ , and the influence of irrigation, compared to the other two ‘wetter’ blocks. Thus ‘block’ differences demonstrated the relative importance of water availability in weed and tree interactions. The results from Blocks 1 and 2 are consistent with ‘well-watered’ or irrigated sites (Richardson 1993, Neary *et al.* 1990) where the effect of weeds on soil water availability is usually small. Those from Block 3 support conditions where water availability is strongly depleted in the presence of grass due to summer rainfall deficits, high water use by the grass, and tree root systems restricted to surface horizons (Nambiar and Zed 1980, Sands and Nambiar 1984, Smethurst and Nambiar 1989, Crunkilton *et al.* 1992, Frochot *et al.* 1995).

At this site, the impact of weed presence on soil water availability depended on water table depth, and stage of growth and season. During the first year of tree growth weeds reduced θ (0 – 25 cm) by 8% on average across the site. Differences were greatest during the first six months of tree growth with θ increasing over winter then declining during spring and summer, with high variability throughout. W_a was generally high throughout the period. However, results from Block 3 showed that W_a declined under grass to $< 5\% W_a$ (0 – 25 cm depth) or $< 40\% W_a$ (0 – 100 cm) during three periods in the first year. These periods were at tree age 3, 8 and 13-16 months (January 1997, July and August 1997, and November 1997 – February 1998, respectively). Attiwill and Adams (1996) showed that serious reductions in plant growth occurred when $> 80\%$ of W_a was removed. In this study W_a was depleted to similar levels in the surface soil (0 – 25 cm) suggesting that young trees could have experienced moderate to severe water stress during these times unless they could access moist soil at depth. In contrast, Blocks 1 and 2 had high levels of water availability (0 – 25 cm), which would have been readily available for tree and grass use. Water stress and drought risk in these Blocks was therefore low.

In the second year of tree growth θ (0 – 25 cm) of W and WF treatments responded similarly, but with much higher fluctuation than in year one. θ was lowest during late summer / early autumn (March 1998), consistent with conditions experienced in southern Australia after a long, warm, dry summer (Cromer 1980, Boomsma and Hunter 1990). During the same period however, irrigation inputs were lower, due to concerns regarding increasing salinity from the irrigation water source.

There was an overall decline of θ with time during the second year of growth, which was probably due to the increasing demand for water by *E. globulus*, along with increased canopy interception. Canopy closure had occurred by age 16 months in some WF plots. This effect was probably intensified due to the high planting density (1600 stems ha⁻¹) and intra-specific competition for water would have been increasing in surface soil. θ in WF treatments was always greater than W treatments. This pattern of decreasing soil water content over time under trees has been observed in other studies (Eastham *et al.* 1990). For example, young *P. radiata* growing on deep sands in South Australia was able to deplete stored soil water throughout the profile within 7 years of planting (Mitchell and Correll 1987). Decreasing soil water tables have also been reported over time under many perennial tree crops (Greenwood 1985) and has led to increasing research on the use of fast growing trees, such as eucalypts, for lowering saline soil water tables on a regional basis (Greenwood 1992).

H. lanatus is a cool season grass, and was dormant during the second summer after planting; therefore water use by grass at this time was low. Many grasses however, have the capacity to respond to summer rains when they occur (Elliott and White 1987, Dodd *et al.* 1998, Dunne and Parker 1999). Grasses that are summer active can continue to deplete water during the drier summer period (Johnston 1992, Dear and Cocks 1997) thereby increasing water stress of young tree seedlings. Plant density (Pabst *et al.* 1990, Momen *et al.* 1992) and stage of growth are other important factors. It was apparent that a mulch effect was present, particularly after flowering, seed set and maturity, which would have been partly responsible for the similarity of θ between W and WF treatments during summer 1996/97 and then during subsequent

grass regrowth in the second year. Another reason for the similarity between W and WF treatments during the second year would have been the increasing influence of *E. globulus* in WF treatments on surface soil water availability.

H. lanatus responded strongly to nitrogen application (N_{High}) with the development of a dense, vigorous sward. The earlier onset of seed set and flowering by the fertilised grass compared to unfertilised grass during spring 1997 suggests that a water limitation was probably induced by this vigorous grass growth. A depletion of θ in fertilised relative to unfertilised W plots during this period was evident in Block 3 (Figure 5.15) but this was masked by the high water availability in Block 1 and 2. It would therefore appear that more vigorous grass growth was associated with higher water use. In wheat (*Triticum* spp), increased early growth rates induced by nitrogen fertiliser led to more rapid extraction of soil water, leading to early ‘haying off’ when water became limiting (Baldock and Leonard 1998). The greater use of water during spring in this experiment reduced the availability of water for young seedlings during this important growing period, and also led to lower soil water storage during the summer. This was shown to occur in the second spring and summer after planting when the grass sward was fully developed. Where fertiliser is applied to young trees in the presence of grass weeds, the induced vigorous shoot growth of the grass can cause shading of tree seedlings. This is also a common effect in vigorous pastures and results in suppression of low growing broad-leaved species such as *Trifolium repens* (White clover) (Turkington 1990, Dear *et al.* 1998).

Grass productivity in southern Australia is reduced by lack of moisture in summer and low temperatures in winter (Johnston 1992). Increased availability of water (eg. irrigation) can increase pasture productivity, and this often provides an effect additive to N-fertiliser application (Whitehead 1995). In this experiment, the response of *H. lanatus* to high irrigation was only apparent in the unfertilised plots in Block 3 where I_{High} had higher θ (0 – 25 cm) than I_{Low} treatments. This was not evident in the 25 – 100 cm depth. In the other blocks, there was no response to I_{High} due to the higher availability of water. Under low irrigation in Block 3, growth of *H. lanatus* was poorer, particularly in N_{Zero} treatments, where both water and nutrient availability was low. The competitive interaction between *H. lanatus* and *A. vulgaris* changed under these conditions such that the grass was less able to compete with *A. vulgaris*. Under favourable soil nutrient and water conditions (Blocks 1 and 2) growth of *H. lanatus* was rapid which enabled it to develop into a dense vigorous sward and shade out *A. vulgaris* (Nielsen 1998).

Many tree species respond strongly to irrigation (Snowdon and Waring 1991), including fast growing eucalypts (Stewart *et al.* 1986, Myers *et al.* 1999), especially where plant available water is low or seasonal water demand is high (Pereira *et al.* 1989, White 1996). Responses to irrigation are also common in conditions of apparently high water availability (Cromer 1980). In this experiment, there was no tree response to irrigation except at age three months when there was a non significant increase in crown cross sectional area (cm^2) (data not presented). In Block 3, I_{High} increased θ in both W and WF plots. In weedy plots this resulted in increased growth of the trees compared to in the I_{Low} treatment, though this was not significant. Tree growth rates in WF plots receiving I_{High} actually decreased relative to those

receiving I_{Low} . Many eucalypts cannot tolerate excess soil water (Connell 1998) due to a reduction in oxygen concentration, changed pH and altered nutrient availability. While water logging may have been a contributing factor at depth ($> 1\text{m}$), water salinity along with induced micro-nutrient deficiencies were probably more important.

A response to N-fertiliser by *E. globulus* only occurred in the presence of weeds (see Chapter 4). The lack of positive growth responses to N in WF plots was possibly related to induced deficiencies of other nutrients such as copper and zinc (Cromer and Turnbull 1994). In N-fertilised weedy plots, tree growth increased when I_{High} was applied. This increased growth was most apparent in Block 2 where the water table was also shallowest and θ (0 – 100 cm) greatest. Therefore high water availability and high rates of N-application (300 kg N ha^{-1}) were required for a positive response to N-fertiliser by both the weeds and the trees. This suggests that a water by nitrogen interaction was occurring (Collet *et al.* 1996a). The probable mechanism was through increased nitrogen availability and / or nitrogen uptake at high θ (Nambiar 1990, Erskine *et al.* 1996).

It had been anticipated that soil water would be a limiting resource and that competition would occur between the trees and the grass, especially while roots were confined to the upper soil layers during the first year of tree growth. The impact of weeds was greatest during the first year of tree growth when tree water use was low and the influence of the grass was greatest, even under conditions of high water availability. A similar observation was made in an effluent-irrigated plantation where vigorous weed growth occurred prior to canopy closure under conditions of high

water and nutrient availability (Myers *et al.* 1999). In this case the weeds are utilised to increase water use and buffer against effluent leaching losses prior to full site occupancy by trees. There, the association between high water availability and reduced growth of trees in the presence of weeds was considered to be mainly due to competition for light and nutrients, although water deficits can occur if the irrigation interval is too long (Myers *et al.* 1999). The increasing focus on tree-based amelioration of high water tables in Australia will need to account for weed competition during establishment. The effect of high water availability on weed – tree interactions in this study will help develop guidelines for management.

5.5 Conclusions

This study tested the hypothesis that soil water would be depleted by grass, which would explain the suppression of *E. globulus* growth at this site. However, due to the dominating influence of the high water table in Blocks 1 and 2, direct competition for soil water between grass and young trees was small and short-lived. Available soil water, including in surface soil (0 – 25 cm), was within reach of the root systems of both trees and weeds from an early age during most of the study. In Block 3, where the water table was deeper, the impact of weeds was greater and therefore competition for water was more important in the weed – tree interaction. This is consistent with the majority of weed competition studies in Australia where water was the dominant resource competed for between weeds and young trees. Vigorous grass growth with increased leaf area has high water requirements. Depletion of available water during spring and early summer by the grass was an important determinant of the early growth of *E. globulus* in Block 3.

The intensity and duration of competition for water between the grass and young *E. globulus* was influenced by soil water availability, the relative rooting depth of the species, depth to the water table, weed biomass and tree age. On the basis of results from Block 3, the timing of greatest water competition by *H. lanatus* was during the first 12 – 15 months of growth. While trees were young with root systems confined within the grass root zone and not able to access water at depth, the potential for water stress was greatest. The low W_a in Block 3 suggests that this may have occurred. However, measures of plant water stress, are required to determine whether the depletion of soil water resulted in tree water stress. This is addressed in the next chapter.

6. Influence of *H. lanatus* on the water relations of young *E. globulus*

6.1 Introduction

Weed-induced water stress is a major factor limiting growth of young trees across a wide range of sites and environments (Eissenstat and Mitchell 1983, Sands and Nambiar 1984, Cole and Newton 1986, Fensham and Kirkpatrick 1992, Collet *et al.* 1996b, Mitchell *et al.* 1999). Due to their vigorous growth and extensive root systems, grasses can deplete soil water, especially in the surface soil (Nnyamah and Black 1977, Elliot and White 1987, Crunkilton *et al.* 1992, Palaez *et al.* 1992, Collet *et al.* 1996a). In regions where levels of available water is limited, for example due to summer rainfall deficits, competing grasses often exacerbate drought stress of young trees (Margolis and Waring 1986, Perry *et al.* 1994). In southern Australia, the period of greatest risk of weed-induced water stress is during the establishment phase, particularly during the first summer after planting (Sands and Nambiar 1984, Boomsma and Hunter 1990), while tree roots are restricted to the upper soil profile, and in direct contact with neighbouring grass.

As the trees become established, their deeper root systems gain access to soil water below the 'zone of influence' of the weeds, and water stress generally declines (Hinkley *et al.* 1981, Sands and Nambiar 1984, Costantini 1989, Woods *et al.* 1992, Kellas *et al.* 1995, Hadryanto 1994). It is possible to have the A horizon, which contains a large proportion of the tree roots, experiencing drought without the young trees experiencing direct moisture stress (Neary *et al.* 1990). The duration of

susceptibility to weed-induced water stress therefore depends upon the availability of water beyond the weed root system, and the rate at which tree roots access this water.

When weeds are removed, it is common for an associated increase in soil water content and improvement of tree water relations (Preest 1977, Nambiar and Zed 1980, Smethurst and Nambiar 1989, Hadryanto 1994, Dodd *et al.* 1998, De Montard *et al.* 1998). Such changes in plant water relations are expressed in measurable changes in leaf water relations. One of the most reliable and widely used methods of measuring leaf water relations is leaf water potential (ψ_L) (Kozlowski and Pallardy 1997). This method estimates the leaf potential or negative pressure that creates tension and pulls water towards the leaf. It is an instantaneous measure of soil water limitation (White *et al.* 1999). A more negative pressure indicates greater work required to pull water from the soil, indicating lower water availability and therefore greater water stress. Many studies have demonstrated high correlations between ψ_L and the depleted levels of available soil water in the presence of grass (Sands and Nambiar 1984, Margolis and Waring 1986, Pabst *et al.* 1990, Collet *et al.* 1996a, White *et al.* 1996, Mitchell *et al.* 1999).

Growth of young trees is very sensitive to weed-induced water stress (Nambiar 1990, Pereira and Pallardy 1989). When moderate water stress occurs, leaf expansion rates become inhibited (Pereira and Kozlowski 1976) resulting in reduced leaf area index and light interception (Beadle *et al.* 1995) and therefore reduced growth. Under severe water stress, a decrease in photosynthetic efficiency occurs (Jarvis and Leverenz 1983), cell division ceases and damage begins to occur to membranes and

enzymes. Eventually, prolonged water stress leads to overheating and finally death (Beadle 1997).

Water stress in *E. globulus*, is considered to occur when pre-dawn leaf water potential (ψ_{\max}) is more negative than -0.55 MPa (White 1996). Above this level, trees have adequate levels of available water such that growth is unrestricted. In a study of *E. globulus* water relations, minimum values of ψ_{\max} in severely-stressed trees (rainfed) were -2.4 MPa (White *et al.* 1996). Collet *et al.* (1996b) found high stress values (-1.7 to -3.0 MPa) for young sessile oak (*Quercus petraea* (Mattus.)Liebl.) when growing with grass during summer. Young *Pinus radiata* growing with grass became severely stressed during summer with $\psi_{\max} < -2.0$ MPa (Sands and Nambiar 1984).

In addition to soil water availability, many environmental and plant factors influence water use including: climatic conditions (light intensity, evaporative demand, vapour concentration gradient between the leaf and air, temperature and wind), and canopy structure, area and exposure, stomatal control and root access to soil water. *E. globulus* uses strong stomatal control of transpiration rather than osmotic adjustment, to respond to soil moisture stress (White 1996). White *et al.* (1999) found that stomatal conductance (g_s) was significantly reduced in rainfed trees (compared to irrigated trees with ample water) when ψ_{\max} was less than -0.50 MPa. This was also reflected by its fast recovery after soil re-wetting. Consequently g_s is a good measure of leaf water relations and plant water use. Both g_s and ψ_{\max} can be used to indicate whether water stress is occurring in a young tree plantation. In addition, the

measurements can indicate the timing and duration, and extent to which grass is contributing to this stress.

Three main processes are involved in plant water use: (1) evaporation of water intercepted by the plant (physical process), (2) transpiration involving the uptake of soil water by the roots and transfer through to the leaves (physiological process) and (3) evaporation from the soil surface. Transpiration dominates plant water use accounting for more than 98% of the water uptake. For soil recharge to occur, water inputs need to exceed water transpired and evaporated. This is common in winter in southern Australia, however, during summer, evaporative demand usually exceeds soil water inputs. Therefore, trees rely on stored soil water reserves for water supplies over extended periods (Honeysett *et al.* 1992).

In this study at the time of planting, bare soil dominated the site, and water use by tree seedlings would have been minimal. Most of the water inputs (rainfall and irrigation) would have infiltrated the soil and increased the soil water storage (most irrigation was applied between 1800 and 0600 hours to minimise losses by evaporation). Evaporation of water from the moist soil would be significant however, due to the windiness of the site and high temperatures achieved in the bare surface soil especially during summer.

Tree water use (actual evapo-transpiration, E_t) can be estimated by Class A pan evaporation (E_p) (Worledge *et al.* 1998, Myers *et al.* 1999). This is a less accurate method of estimating tree water use than direct measurement of soil water content or process-based modelling and soil water balance (Myers *et al.* 1999). However it has

been suggested that $\max E_t$ is close to or a little above E_p over a wide range of Australian environments and is a robust estimate of E_t over an annual cycle for closed canopies of *E. globulus* or *E. nitens* (Worledge *et al.* 1998).

Crop factor (k) is the ratio of plantation water use (E_t) to pan evaporation (E_p). In South Australia under conditions of high E_p , it was demonstrated that stand water use approximated E_p within three years of planting (Shaw *et al.* 1996). In an irrigation study of *E. nitens* and *E. globulus* in Tasmania (Worledge *et al.* 1998), k was 0.74 at age two years, 0.9 at three years and approximately 1.0 following canopy closure at age four years (White *et al.* 1996). In an older *P. radiata* plantation (aged 10 – 14 years) k values varied between 0.88 and 1.19 (Myers and Talsma 1992). The highest rates were in the irrigated and fertilised treatments and were directly proportional to foliage mass (Myers and Talsma 1992).

While annual water use can be approximated by E_p , seasonal variation does occur and E_p can vary substantially with changing evaporative demand (Myers *et al.* 1999). In an irrigation trial, early age (1 – 2 years) transpiration rates for *E. globulus* were up to 8 mm day⁻¹ (80 000 L ha⁻¹ day⁻¹) in spring / summer compared to 0.5 mm day⁻¹ (5000 L ha⁻¹ day⁻¹) in winter when rainfall will usually exceed tree water use capacity, allowing soil water recharge to occur (Myers *et al.* 1999). In a rainfed experiment at low altitude (annual rainfall 900 – 1130 mm), five-year-old *E. nitens* had maximum E_t rates of 5 mm day⁻¹ in summer, while in winter E_t was 1 mm day⁻¹. This is well within the range of E_t of other stands of eucalypts and temperate forest stands during the summer period (Honeysett *et al.* 1992). E_p is generally low in winter, however E_t may exceed E_p under favourable atmospheric conditions. In

contrast, E_p is usually high in summer, but E_t may be $< E_p$ due to stomatal control of transpiration, as vapour pressure deficit increases during periods of high evaporative demand.

In weedy plots in this study, it was clear that grass strongly influenced water relations. By tree age five months, grass ground cover approached 80% and tree growth was significantly suppressed thereafter. In an effluent irrigation study Myers *et al.* (1999) found that grass contributed more than trees to water use during the first year. They estimated k for grass as 0.5 for the first two years of the study (Myers *et al.* 1999). Other researchers have found higher values (up to $k = 0.8$) for full cover perennial pastures on an annual basis. Data from Myers *et al.* (1999) showed that grass used up to 4 mm day^{-1} during summer and as little as 0.5 mm day^{-1} during winter. Total water use for the year was 426 mm yr^{-1} . In the current study, during the summer dormancy (after flowering and seed set) grass water use was assumed to be zero. These figures are consistent with estimates by White *et al.* (2000). Vertessy (2000) reports that E_t for grasses can be up to 650 mm yr^{-1} .

This chapter examines the water relations of *E. globulus* in the presence and absence of grass and relates the findings to the soil water characteristics described in the previous chapter. The objective was to determine (a) whether the presence of grass induced significant moisture stress in *E. globulus* at this site, (b) how these effects were exhibited, and (c) the importance of these effects under the irrigation and fertiliser treatments.

6.2 Methods and materials

6.2.1 Leaf water potential

Leaf water potential (ψ_L) of *E. globulus* was measured on seven occasions between March 1997 and March 1998 (tree age five – 18 months) using the pressure chamber method (Scholander *et al.* 1965) (Model 1002, PMS Instrument Co., Corvallis, Oregon) (Figure 6.1). Four treatments were measured: I_{High} W and I_{High} WF, and I_{Low} W and I_{Low} WF (all receiving N_{High}). The youngest, fully expanded leaf (YFE) was sampled from each of three trees in each treatment. These were used to estimate pre-dawn (ψ_{max}) and midday (ψ_{min}) leaf water potential. Leaves were sampled from the top third of the crown. Measurements for both were taken on the same day except for the December 1997 measurements. As the number of leaves on *E. globulus* seedlings growing in weedy plots was low (8 – 10 pairs) from age five to 12 months, care was required to minimise leaf removal and impact on future growth. After this time most seedlings in weedy plots had a good selection of leaves for sampling. Juvenile leaves were sampled for all treatments until spring 1997 (age 13 months). After this time samples from trees in weed-free treatments were from adult leaves.

6.2.2 Stomatal conductance

Stomatal conductance (g_s) was measured once on 5th February 1998 (tree age 16 months). On each leaf sampled, g_s was measured on both surfaces (abaxial and adaxial) of the leaves using a Li-1600 steady state porometer (Li-Cor Inc. Lincoln Nebraska). Three trees from the same four treatments used for leaf water potential studies (I_{High} W and I_{High} WF, and I_{Low} W and I_{Low} WF (all receiving N_{High})), were measured using one leaf selected from two aspects (East and West) within each of three canopy layers corresponding to upper, middle and lower thirds of the crown by



Figure 6.1 Pressure chamber apparatus used to determine leaf water potential (photo: D. Worledge.)

depth. The light environment between canopy layers of the weedy trees was similar as they were still small seedlings. Only recent, fully expanded leaves were selected. Stomatal conductance per unit leaf area (g_s) was calculated as the sum of that measured on both sides of the leaf. Measurements were done at two times (0800 and 1030 hrs AEST) and all the trees were within Block 2. This block was chosen as the water table was at a uniform depth for both the I_{High} and I_{Low} treatments.

6.2.3 Water balance and water use

An approximation of water use by grass and trees in Block 3 was calculated during one period in the study (winter 1997) that corresponded with the incidence of water stress (18 May 1997 to 30 July 1997, a period of 75 days). These calculations were based on a water-balance approach where inputs and outputs were defined and appropriate values allocated. In this way, the importance of the competing grass on

the soil and plant water relations at the site could be derived. The water balance for a young plantation at this site is depicted in Figure 6.2.

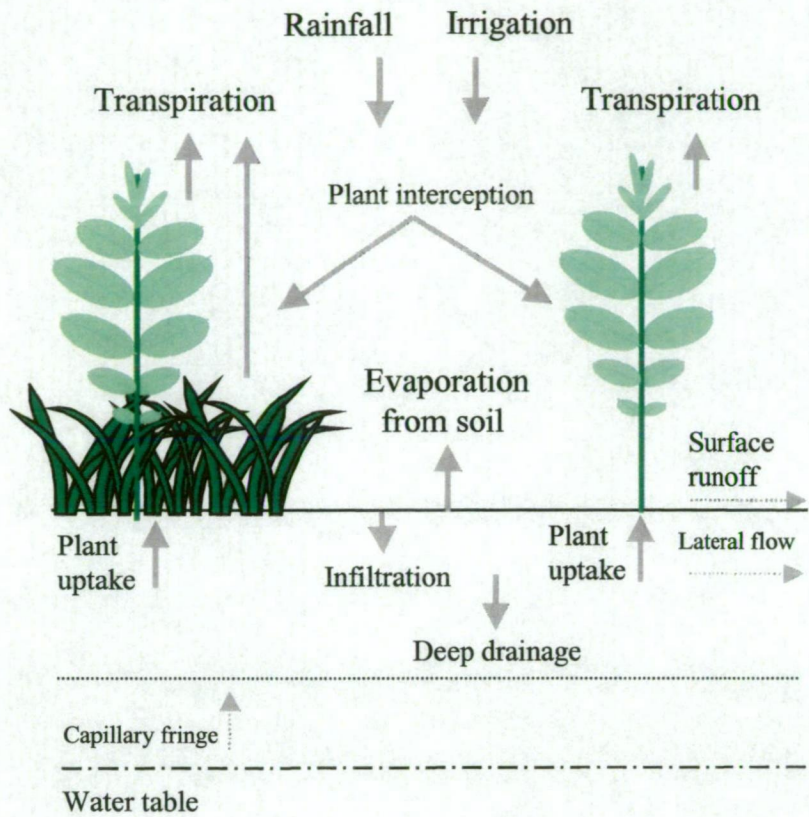


Figure 6.2 Water balance for the grass – *E. globulus* system at the site.

Using data from Block 3 and treatment $I_{Low} N_{High} W$ (grass ground cover, tree growth, irrigation records, soil water content), along with meteorological data from nearby weather station at Hobart airport (rainfall, evaporation), basic inputs and outputs could be defined for the system. In the sandy soil at this site, surface flow and lateral flow would have been negligible. The shallow water table fluctuated according to water inputs, both from within and outside the plantation: the associated capillary fringe also fluctuated (up to 50 cm above the water table). In Blocks 1 and 2, the shallow water table had a large influence on the soil water availability in the

surface 1 m, while in Block 3, the water table was less influential. Data on plant available soil water content (W_a) at the start and end of the period, provided estimation of changes in soil water storage. *H. lanatus* ground coverage was approximately 100%, during this period, therefore it was assumed that evaporation from the surface soil was nil. A conservative crop factor value ($k = 0.5$) was estimated for *H. lanatus* water use, equating with 0.6 mm day^{-1} . Young *E. globulus* growing within grass plots had very low leaf areas, therefore k was estimated to be very small ($k < 0.05$) for the first year of growth. This equated with 0.06 mm day^{-1} water use during the period.

6.2.4 Data analysis

Leaf water potential

The GENSTAT ANOVA procedure (Genstat 5 Committee 1994) was used to analyse leaf water potential for each treatment (4 treatments x 3 blocks) using the following single factor model (Equation 6.1).

$$\Psi_{L,ij} = u + T_i + e_{ij} \quad (6.1)$$

Where $\Psi_{L,ij}$ was leaf water potential of the j^{th} leaf from the i^{th} treatment, u was the sample mean, T_i and e_{ij} treatment and residual variance.

Stomatal conductance

The GENSTAT ANOVA procedure (Genstat 5 Committee 1994) was used to analyse each set of stomatal conductance data (4 treatments x 3 trees) using the

following single factor model (Equation 6.2). Aspect and canopy level was combined as there was no significant difference between them.

$$g_{s,ij} = u + T_i + e_{ij} \quad (6.2)$$

For the two times (0800 and 1030 h), $g_{s,ij}$ was the stomatal conductance of the j^{th} leaf from the i^{th} treatment, u was the sample mean, T_i and e_{ij} treatment mean and residual variance. The data was also analysed as a two-way ANOVA (factorial) to determine whether any interactions between irrigation level and weeds occurred.

Leaf water potential relationship with soil water content

E. globulus leaf water potential measurements were regressed against soil water content for each measurement date (seven occasions between March 1997 and March 1998). Soil water content in Zone 1 (0 – 25 cm), Zone 2 (25 – 100 cm) and Zone 1 and Zone 2 combined were tested as explanatory variables, using both linear and non-linear curves.

6.3 Results

6.3.1 Leaf water potential

The *E. globulus* trees experienced low to moderate water stress across the site except in July and November 1997, when I_{Low} W was the most stressed treatment (Table 6.1). Pre-dawn leaf water potential (ψ_{max}) of WF treatments ranged from – 0.25 to – 0.65 MPa from age five to 17 months. ψ_{max} of the W treatments were similar to those in WF treatments except at age nine and 13 months when they indicated much higher stress (– 1.12 and – 0.90 Mpa, respectively) for I_{Low} W treatments.

From age nine months (July 1997), ψ_{\max} of W were consistently more negative than for WF treatments, but this was significant only for the 12 months (October 1997) measurement ($p < 0.05$) in which only low water stress occurred (-0.25 to -0.42 MPa). There was no significant difference between treatments at 9 months even though there had been no rain or irrigation for two weeks. Moderate water stress was indicated in I_{Low} W and was predominantly due to weedy trees in Block 3. Following low stress at age 12 months, moderate water stress was indicated at 13 months (November 1997) in W treatments. Block 3 values again contributed the most to this result. Figure 6.3 shows ψ_{\max} results in individual plots.

Table 6.1 *E. globulus* pre dawn (ψ_{\max}) and midday (ψ_{\min}) leaf water potential. For each date figures appended by the same letter are not significantly different ($p < 0.05$). Values beyond the critical pre-dawn leaf water potential (-0.55 MPa) value are indicated in bold type.

Tree age	Date	Irrig.	ψ_{\max} (MPa)				ψ_{\min} (MPa)			
			W		WF		W		WF	
5 months	Mar 1997	I_{Low}	-0.42	a	-0.40	a	-1.33	a	-1.20	a
		I_{High}	-0.33	a	-0.32	a	-1.30	a	-1.27	a
9 months	Jul 1997	I_{Low}	-1.12	a	-0.65	a	-1.69	a	-1.30	a
		I_{High}	-0.79	a	-0.62	a	-1.37	a	-1.21	a
12 months	Oct 1997	I_{Low}	-0.42	b	-0.25	a	-1.69	b	-1.22	a
		I_{High}	-0.42	b	-0.28	a	-1.84	b	-1.51	ab
13 months	Nov 1997	I_{Low}	-0.90	a	-0.50	a	-1.83	b	-1.09	a
		I_{High}	-0.69	a	-0.47	a	-1.69	ab	-1.23	ab
14 months	Dec 1997	I_{Low}	-0.64	b	-0.50	a				
		I_{High}	-0.66	b	-0.50	a				
16 months	Feb 1998	I_{Low}	-0.44	a	-0.43	a	-1.77	a	-1.57	a
		I_{High}	-0.52	a	-0.51	a	-1.80	a	-1.80	a
17 months	Mar 1998	I_{Low}	-0.65	b	-0.42	a	-1.69	a	-1.46	a
		I_{High}	-0.66	b	-0.61	ab	-1.72	a	-1.59	a

6.3.2 Stomatal conductance

There was no significant difference in stomatal conductance between I_{High} and I_{Low} and W and WF treatments, and no significant interactions ($p > 0.05$). However there was still a trend towards higher conductance in WF treatments. The g_s of weedy trees (at both levels of irrigation) was $270 \text{ mmol m}^{-2} \text{ s}^{-1}$ at 0800 h, decreasing to $196 \text{ mmol m}^{-2} \text{ s}^{-1}$ by 1030 h. The trend was similar for weed-free trees though at higher levels indicating higher rates of transpiration. The g_s of WF trees receiving I_{Low} was 40 – 50 $\text{mmol m}^{-2} \text{ s}^{-1}$ higher than weedy trees (Figure 6.4). The g_s of WF trees receiving I_{High} was much greater ($> 400 \text{ mmol m}^{-2} \text{ s}^{-1}$ at 0800 h) than those receiving I_{Low} .

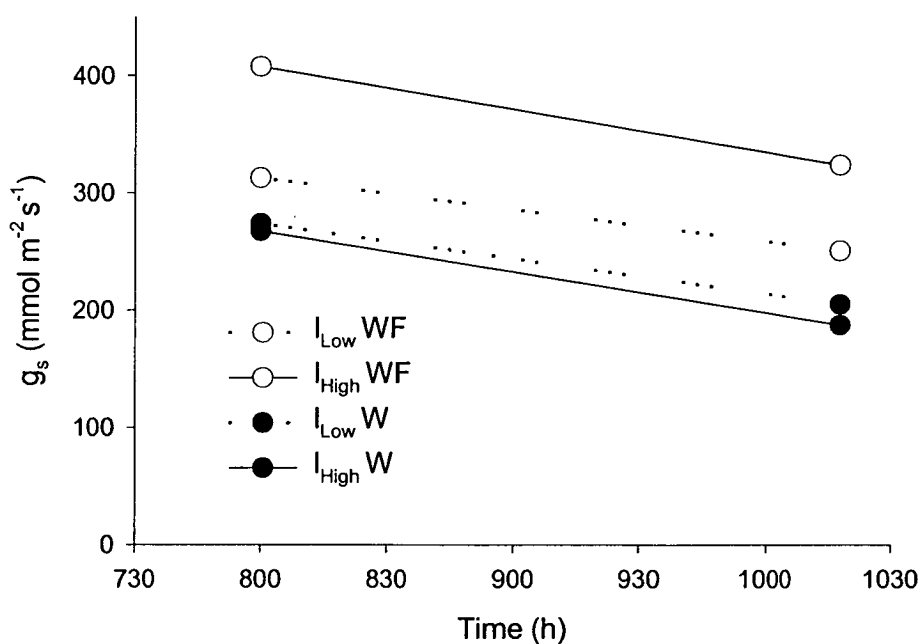


Figure 6.4 *E. globulus* g_s on 05/02/98 (age 16 months) at 0800 and 1030 hrs.

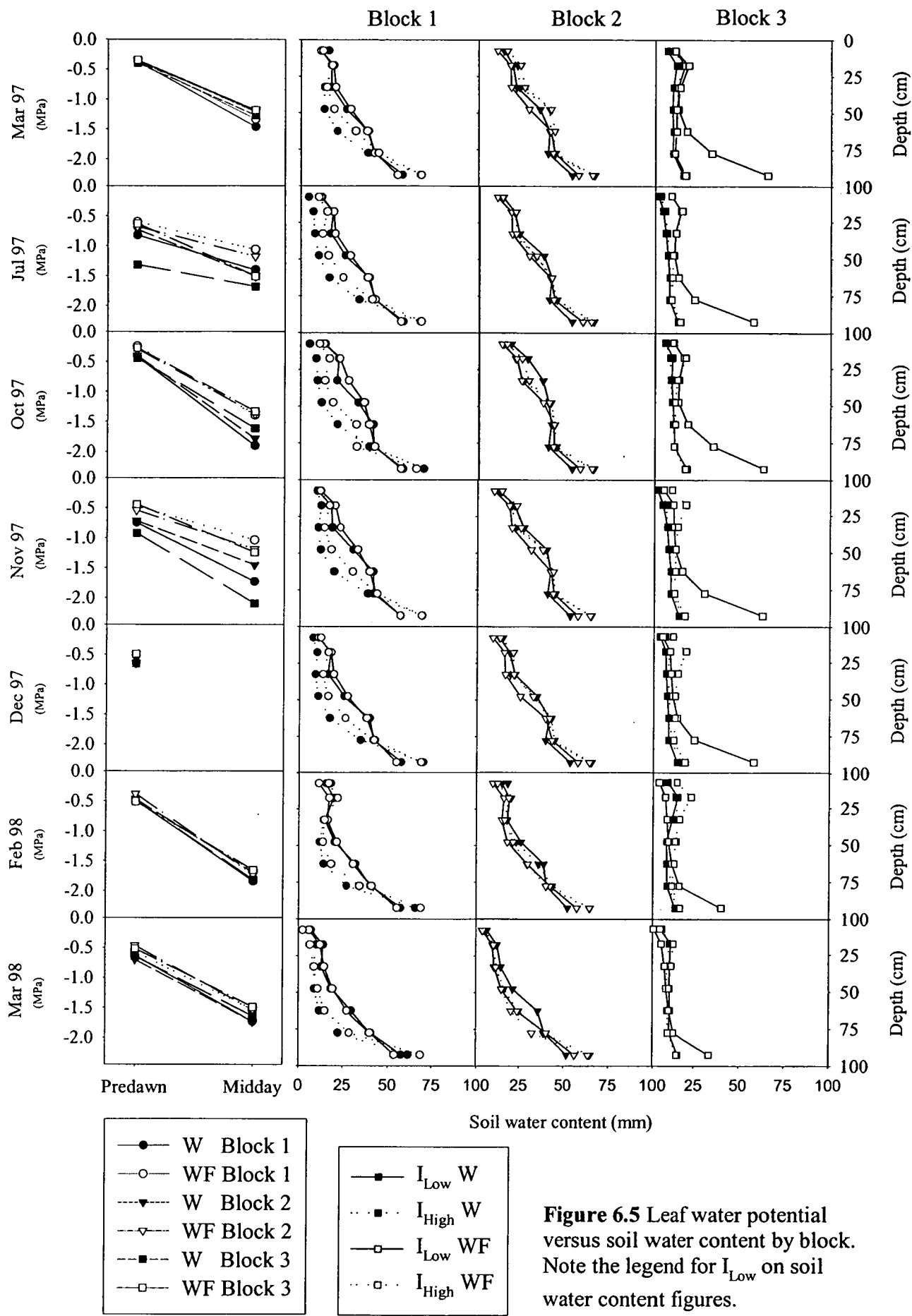
6.3.3 Relationship between leaf water potential and soil water content

Pre-dawn and midday leaf water potential for each date is presented in Figure 6.5 along with the soil water content (θ) profiles down to 1 m depth, for each weed and

irrigation treatment by block. The leaf water potential curves for each W and WF treatment have three lines (one for each block) linking ψ_{\max} and ψ_{\min} measurements. It can be seen that treatment behaviour and ranking is similar throughout the study period, indicating only low to moderate stress, with weedy treatments generally more stressed than weed-free treatments. The water stress experienced in Block 3 treatments can be clearly seen in late July and November.

The soil water content profiles show differences between blocks in both trend and treatment. In Block 1, I_{Low} had higher θ than I_{High} between 25 and 75 cm soil depth for most of the sample periods. This is due to the deeper sandy profile above the water table in I_{High} than I_{Low} treatments. In Block 2 there was no change in θ between treatments throughout all depths, reflecting its position in the site in relation to the shallow water table. In Block 3 there was much lower θ down to 75 cm depth, due to the deeper sand A horizon and consequent lower water table. This was the main factor affecting ψ_{\max} in Block 3. Weedy plots had lower θ than weed-free plots for most of the measurement period. ψ_{\max} for the WF treatments had a narrower range of values (– 0.25 to – 0.65 MPa) compared to W treatments.

When ψ_{\max} was regressed on θ for Zone 1, Zone 2 and Zone 1 and 2 combined (0 – 100 cm) strong curvilinear relationships were obtained for the $I_{\text{Low}} N_{\text{High}} W$ treatment in Block 3. Relationships for the remaining treatments and Blocks ($I_{\text{Low}} N_{\text{High}} WF$, $I_{\text{High}} N_{\text{High}} W$ and $I_{\text{High}} N_{\text{High}} WF$) were all very weak due to the high soil water content and low stress indicated by ψ_{\max} during the period. A strong relationship for $I_{\text{Low}} N_{\text{High}} W$ was obtained for θ in combined Zone 1 and 2 (0 – 100 cm) and was best



described by a rectangular hyperbola, $r^2 = 0.84$ (Figure 6.6). The best linear model fitted was for the combined zones ($r^2 = 0.60$). Fitting ψ_{\max} against Zone 1 only with a rectangular hyperbola curve provided an $r^2 = 0.90$ (Figure 6.7). A much weaker relationship was obtained for Zone 2, with the best fit using an exponential curve, $r^2 = 0.57$.

6.3.4 Water balance

The approximations relating to water use by the grass and trees in a range of treatments indicated the relative roles each played in water relations at the site during the dry winter period in 1997 (18 May 1997 to 30 July 1997, a period of 75 days). Table 6.2 provides figures of approximate water balance values. Plant available soil water content (0 – 25 cm depth) at the start of the period was 14.1 mm. During this time there was 31 mm rainfall occurring as sporadic events (minimum event < 0.5 mm, maximum event 6.5 mm). There was 93 mm pan evaporation during the period. No irrigation was applied. *H. lanatus* ground coverage was approximately 100%, therefore it was assumed that evaporation from the surface soil was nil. Using a conservative value for k ($= 0.5$) the N-fertilised grass was estimated to use 46.5 mm water during the period. This equated to 0.6 mm day^{-1} water use. Therefore, most of the available soil water stored in the surface soil was exhausted, along with rainfall during the period, at the expense of the young trees. Drainage below this upper soil zone (0 – 25 cm) would have been minimal. At the start of the period there was 67% plant available water in the zone, but by the end there was < 4%.

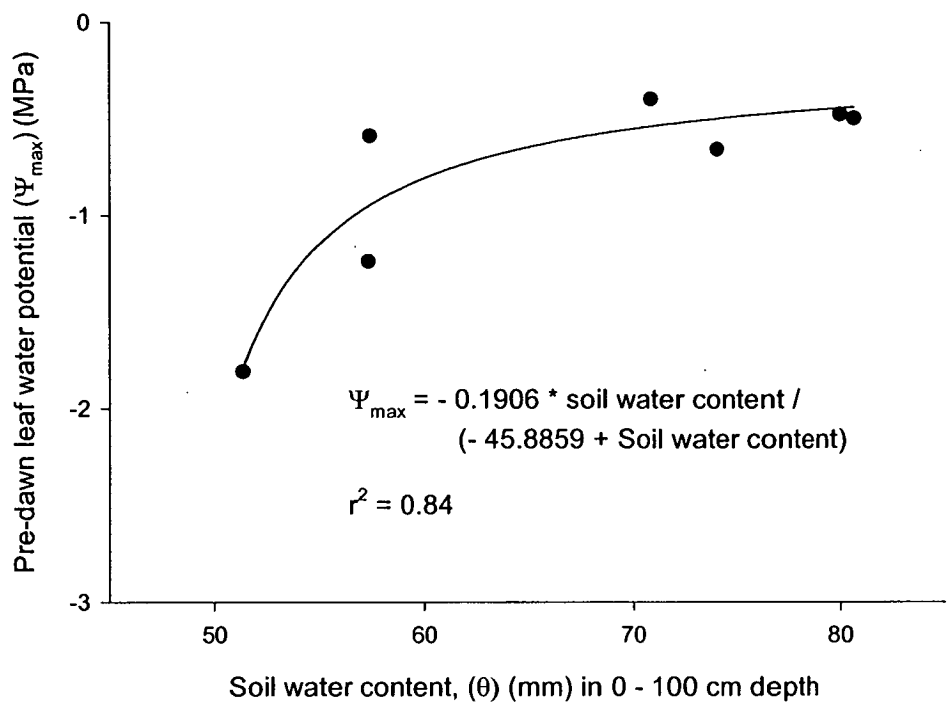


Figure 6.6 Pre-dawn leaf water potential (ψ_{\max}) of *E. globulus* regressed on soil water content (0 – 100 cm depth) for treatment $I_{\text{Low}} N_{\text{High}} W$ in Block 3. Curve fitted is a rectangular hyperbola.

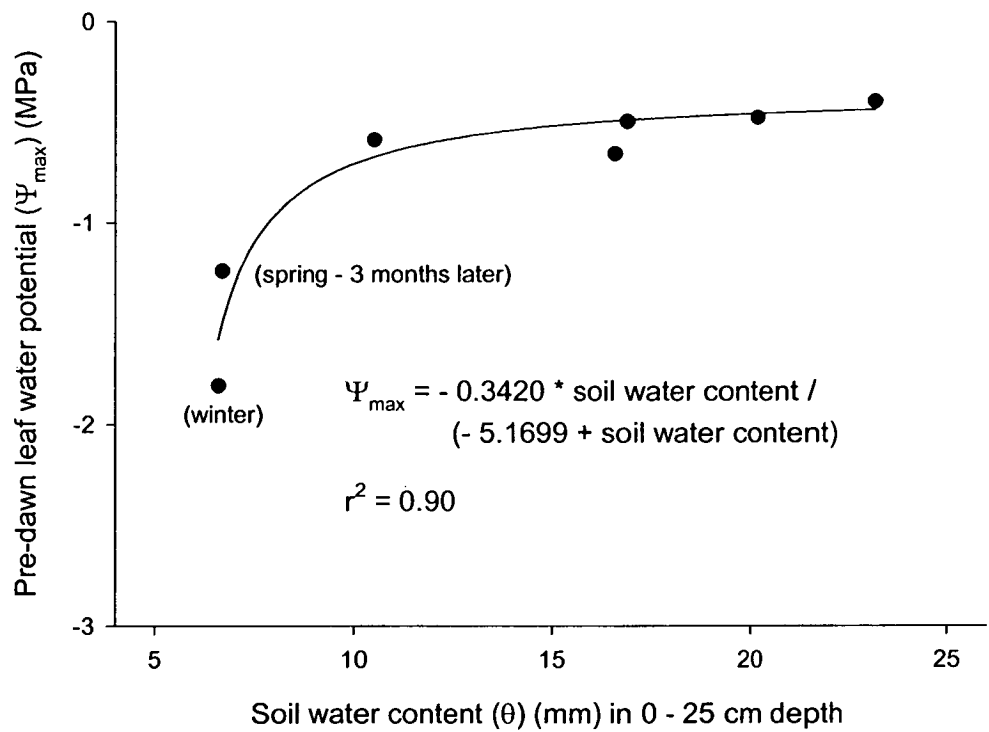


Figure 6.7 Pre-dawn leaf water potential (ψ_{\max}) of *E. globulus* regressed on soil water content (0 – 25 cm depth) for treatment $I_{\text{Low}} N_{\text{High}} W$ in Block 3. Curve fitted is a rectangular hyperbola.

Water use of the young *E. globulus* growing within grass plots was estimated at 4.6 mm during the period. Total plant water use (*H. lanatus* and *E. globulus*) was estimated to be 51 mm during the period, which is greater than the plant available water at the start of the period plus any rainfall additions. Soil water storage in the zone was reduced by almost 95% during the period, therefore the demand for water would have needed to be met from lower in the profile. Evaluating the effects of plant water use on soil water availability for the deeper soil zone (0 – 100 cm) (Zone 1 and Zone 2 combined) shows that water storage was depleted by 50% during the period (Table 6.2).

Table 6. 2 Estimated soil water balance (mm) for a dry 75-day period (18 May to 30 July 1997) (tree age 6.75 to 9.25 months). Crop factor (*k*) for *H. lanatus* = 0.5, *E. globulus* = 0.05

Water balance (mm)	Winter 1997	
	Soil zone 0 – 25 cm	Soil zone 0 – 100 cm
Soil water content at start	14.1	57
Rainfall	31	31
Irrigation	0	0
Evaporation	93	93
Estimated <i>E. globulus</i> water use	4.6	4.6
Estimated <i>H. lanatus</i> water use	46.5	46.5
Estimated total plant water use	51.1	51.1
Soil water content at end	0.8	28.5
Change in soil water storage	-13.3	- 28.5
Deep drainage	0	

6.4 Discussion

This research has shown that *E. globulus* growing with *H. lanatus* experienced low to moderate stress ($\psi_{\max} < 0.55$ MPa) on a number of occasions during the two-year study. These periods of stress were isolated to those trees growing in the driest block (Block 3), while the remainder of the site in general experienced only low stress. Factors determining the intensity, timing and duration of weed-induced water stress include site water availability, evaporative demand, weed density and biomass (Momen *et al.* 1992), age and development of the trees (Nambiar and Sands 1993) and the relative root volume occupied by each species (Aldrich and Kremer 1997). In southern Australia, water stress during the establishment phase is considered to occur when the trees are young and have roots restricted to the upper soil profile, in direct contact with grass root systems. Stress can be particularly severe during the first summer after planting (Sands and Nambiar 1984, Boomsma and Hunter 1990). The development of water stress in Block 3 during the summer period is consistent with this. Rainfall deficits during spring / summer, coupled with low soil water storage, deep water tables, and vigorous grass growth leads to depletion of soil water and consequently stress of the young trees (Squire *et al.* 1977, Nambiar and Zed 1980, Sands and Nambiar 1984, Richardson *et al.* 1996, Collet *et al.* 1996b). Competition for water is therefore considered to be a major reason for suppressed tree growth in the presence of grasses, throughout southern Australia (Boomsma and Hunter 1990, Richardson 1993) and other parts of the world where mediterranean climates occur (Collet *et al.* 1996b).

Studies often suggest that grass and woody plants use water from different parts of the soil profile (Sands and Nambiar 1984, Trlica *et al.* 1985, Brown and Archer 1990, Hadryanto 1994, Weltzin and McPherson 1997, De Montard *et al.* 1998, Dodd *et al.* 1998). Walter's two-layer model proposes that competition for the same pool of water should be limited as trees have access to water through deeper more extensive root systems (Dodd *et al.* 1998). The central agroforestry hypothesis, where the agricultural crop or pasture is the focus of management, states that trees must make use of resources otherwise not used by the crop (Cannell *et al.* 1996). It is during tree establishment however, that tree root systems and resource use is concentrated in the surface soil, resulting in direct competition with other plants such as grass. Therefore the potential for interspecific competition is considered to be greatest during this time, though is dependent on duration of grass presence.

The water relations of trees in Blocks 1 and 2 indicated that W and WF trees experienced low water stress (-0.42 MPa to -0.75 MPa). This reflected the high availability of water via the shallow water table during most of the two year period and was supported by the weak correlations between ψ_{\max} and soil water availability. Soil water in these blocks was less susceptible to depletion by *H. lanatus* compared to Block 3 where the influence of the water table was much lower. The low water stress experienced by trees in Blocks 1 and 2 is consistent with the findings of Neary *et al.* (1990) where grass competition with *Pinus taeda* on a wet spodosol (sandy A horizon overlying a spodic Bh horizon) was investigated. These current results are important in the context of land affected by rising water tables and salinisation in Australia (Johnston 1992) where there is increasing research on the use of fast growing eucalypts to lower such water tables (Greenwood 1992).

At the time of planting, seedlings had a 10 cm root depth (restricted by container length). Some initial water stress may have been experienced, though the irrigation would have minimised its intensity and duration and the total ground cover was still relatively low (20 – 40% at age three months). At age five months, there was still no indication of water stress and by this time, tree root systems would probably have had access to moist soil at depth (especially in Block 1 and 2). Excavation of tree and grass root systems at age eight months demonstrated that both species had easy access to moist soil at 60 cm depth (Chapter 4). Although there were periods when the surface soil dried out, deep root access by the seedlings kept the eucalypt leaf water potentials high. The exception was Block 3 where the moist soil was much deeper (>1.5 m) and probably beyond the extent of tree roots until near the end of the first year of growth.

At age nine months in Block 3, during a winter drought period (winter 1997) soil water content declined significantly and water stress developed (- 1.81 MPa). A second period of stress was detected four months later at age 13 months (spring 1997) when water availability was low during the peak of the growing season (- 1.24 MPa). It was evident that stress experienced by weedy trees in Block 3 during the first year of growth occurred rapidly when rainfall plus irrigation became limiting. This was related to the low buffering capacity of the sandy soil (low water holding capacity) which is prone to experience drought periodically during the growing season (Neary *et al.* 1990). Pre-dawn leaf water potential fluctuated widely. Previous studies that have allowed drought periods to develop have shown a strong and rapid decline in levels of available water under grass weeds leading to high levels of stress (eg. *Quercus petraea*) (Collet *et al.* 1996b). Vigorous perennial pastures can

similarly deplete soil water rapidly, following rainfall and develop soil moisture deficits to depth during summer (Johnston 1992, Dear *et al.* 1998). Another factor contributing to tree water stress in Block 3 was the relatively high water use of the grass, and the low root density of the young trees. This low root density prevented young *E. globulus* from extracting sufficient water in competition with the high root density of the grass, as well as reducing access to water from deeper in the profile.

Measurements of g_s indicated that the weed-free trees receiving high irrigation were transpiring at a much greater rate than trees in the other treatments. *E. globulus* has a high water requirement during establishment to support high rates of canopy development, but this can only be supported with high levels of available water (Greenwood 1985, 1992). The high g_s (in I_{High} WF trees, $407 \text{ mmol m}^{-2} \text{ s}^{-1}$) was consistent with that for *E. globulus* previously observed by White *et al.* (1999), $387 \text{ mmol m}^{-2} \text{ s}^{-1}$. The g_s of W, at both levels of irrigation, was lower than WF trees, indicating increased stress and lower transpiration. This was despite grass dormancy in summer and the shallow water table at this site in Block 2 where the measurements were taken. It is widely accepted that a positive correlation exists between foliar nitrogen concentration and maximum photosynthesis, A_{max} (White *et al.* 1999). As g_s is correlated with A_{max} , g_s can be related to foliar nitrogen status (White *et al.* 1999). As more active leaves have a higher water use requirement, nitrogen availability may be implicated in the stomatal response to grass presence. Differences between treatments also reflect the difference in leaf area between W and WF trees. Healthy trees with large canopies transpire the most water (Kozlowski and Pallardy 1997).

Temperate grasses are commonly limited by lack of soil moisture in summer in southern Australia (Johnston 1992). The low water availability in the surface soil of weedy plots during the second summer after planting in Block 3, was associated with dormant grass and minimal water use. By this time (tree age 14 to 16 months) tree roots would have extended into moist soil at depth, thus supplying adequate water for transpiration. The growth of *E. globulus* can also slow down during summer especially during times of high vapour pressure deficit. This is common in Portugal where VPD can be very high (Pereira *et al.* 1989). The hypothesis that *E. globulus* would grow faster in the presence of grass if irrigated (I_{High}) was not confirmed here. There was high water availability in Blocks 1 and 2 and additional water did not improve tree growth. In Block 3 however, there was improved early growth in response to I_{High} (non-significant, $p>0.05$) and grass growth also benefited.

The water balance calculations for Block 3 indicated that grass was dominating water use in weedy plots during the period May – July 1997. Soil water availability (0 – 25 cm depth) and incident rainfall was effectively exhausted by *H. lanatus* during this period, precluding any recharge at depth. Water use by the small *E. globulus* trees was much lower such that the total demand by the grass required depletion of available water from the 25 – 100 cm depth. This was reduced by 50% during the 75-day period. Such depletion rates indicate the dominance of grass water use, and explain the severity of water stress experienced by young trees in this block.

Fertilised grass (N_{High}) flowered and matured three weeks ahead of unfertilised (N_{Zero}) grass (Chapter 5). The increase in available nitrogen increased grass growth rate and hence demand for water, hastening its maturity during spring (Baldock and

Leonard 1998). This probably contributed to higher water stress in *E. globulus* during this period as well.

A factor influencing water use is plant density (Momen *et al.* 1992). High density has been related to increasing water stress in young trees, eg. *Psuedotsuga menziesii* (Pabst *et al.* 1990). Low grass density (20 – 50% ground cover) on a sandy soil, with adequate summer rains, had little effect on ψ_{\max} of *P. radiata* during the first two years of growth (– 0.4 MPa to – 0.6 MPa) (Smethurst and Nambiar 1989). However, other studies in similar conditions have shown much higher levels of water stress (Nambiar 1984). In the present study, the grass cover was very dense (80 – 100% ground cover) and its biomass high (14 t ha⁻¹) and it would have had a high water requirement, especially during spring and in autumn during regrowth.

The onset of water stress is also related to the timing of re-establishment of grass after tree planting. Crunkilton *et al.* (1992) reported that after planting northern red oak (*Quercus rubra*) into a clear cut area, grass re-invaded during the second year and caused water stress to develop. The duration of the grass cover is related to its longevity, and to its proximity to the trees and its impact on soil water recharge, which are related to tree crop espacement and rainfall respectively. A continued effect of grass on water stress in four-year-old Douglas fir (*Pseudotsuga menziesii*) has been reported (Cole and Newton 1986), in three-year-old *Pinus radiata* (Yunusa *et al.* 1995) and in wide-spaced agroforestry plantings of eight-year-old *Prunus* spp. (Lucot *et al.* 1998).

The growth of trees in weedy plots was significantly slower than weed-free trees, with much lower leaf area, leaf size and branch development. These symptoms are not unlike those expected from water stressed trees. Cell expansion declines as water availability decreases (Chaar *et al.* 1997). Pereira and Kozlowski (1976) demonstrated that leaf expansion rates of *E. globulus* were strongly inhibited by moderate water stress. Shoot elongation rates decreased during summer and were associated with ψ_{\max} of -0.7 to -1.0 MPa (Pereira *et al.* 1989). Similarly, shoot elongation and leaf expansion rates of *Quercus douglasii* H. & A. were related directly to soil water status (Koukoura and Menke 1995). It is concluded that the stress experienced by the trees in weedy plots in this experiment was sufficient to cause slow leaf expansion rates, particularly in Block 3. Cell initiation under conditions of low to moderate water stress, is influenced also by nutritional status.

Evidence of high levels of water stress, and associated depletion of soil water by grass is often used to suggest competition for water, however, this may not be the only factor involved. Zobel and van Buitjtenen (1989) concluded that tree responses to water stress were complex and often determined by interactions with other factors such as nutrients. The likelihood of water supply interacting with nutrient uptake and availability, makes consideration of nutrients an important part of any study of competition for water (Nambiar *et al.* 1984), and various studies have shown that water is not necessarily the main limiting factor in weed-tree interactions. Caldwell *et al.* (1995) attributed the strong suppressive effect of grass on *Pinus taeda* to competition for light and nitrogen. Örlander *et al.* 1996 reported nitrogen as the main factor in grass – *Picea abies* interactions.

6.5 Conclusions

In this study, it was apparent that in Block 3 where higher water stress occurred, the importance of water stress declined with tree age (Sands and Nambiar 1984) such that by age 12 – 14 months adequate access to the water table was achieved.

Provided trees can develop adequate root systems in the second year, water stress due to weeds should decline and competition for other resources such as soil nitrogen, become more important (Woods *et al.* 1992). In Blocks 1 and 2 where soil water availability has been high, measurement of tree water relations indicates that water was not directly limiting growth of the young *E. globulus*. Other factors such as competition for nitrogen appear to have been more important.

The findings from this research indicate that rapid establishment is essential for maximum leaf area development and to enhance canopy closure at the earliest stage. This is also important for plantings aimed at lowering shallow water tables. The effect of sub-optimal weed management during establishment of such plantings will be wastage of substantial human and financial resources targeted to this important land use.

The influence of the water table led to high water availability for the young trees during the two-year study at this site, and trees growing with vigorous grass experienced only low to moderate stress during the study, mainly in the first year of growth. The greatest stress was in Block 3. The periods when stress occurred related to times when soil water content was greatly depleted by the grass. Therefore, there was a need for good weed control particularly in Block 3, where the water table was deeper in the soil profile.

While many studies have shown the direct influence of water stress on tree growth in the presence of weeds, others have reported competition for nutrients, as the main mechanism of weed interference. In general, water was not the main limiting resource for tree or weed growth in this study. It was also not the main resource for which competition occurred. This is backed up by lack of growth responses to I_{High} in the presence of grass (Chapters 4 and 5) and the leaf water potential and stomatal conductance indicating only low to moderate water stress. The influence of soil water availability on nitrogen availability and uptake can be very important and is implicated in the weed - tree interaction at this site. Since there was a response to nitrogen application, but not irrigation in the weedy plots, it is concluded that there was little direct effect on seedling growth due to plant water stress except in Block 3. The issue of soil nitrogen availability will be investigated in Chapter 7 and 8 (Soil and Plant Nutrient Relations).

7. Inorganic N and P in soil solution in a young *E. globulus* plantation as affected by weed control, irrigation and N-fertilisation

7.1 Introduction

The soil solution is the immediate source of most nutrients used by plants (Fisher and Binkley 2000) and its importance has been recognised for a long time (Smethurst 2000). The supply of inorganic or 'available' N, as ammonium (NH_4^+) and nitrate (NO_3^-) to the soil solution often limits forest productivity (Carlyle 1986, Judd *et al.* 1996b, Fischer and Binkley 2000). Available N is supplied by mineralisation and nitrification of organic material, while removal can occur through immobilisation, denitrification, leaching and erosion. These processes are affected by both soil and environmental factors including soil water content, temperature, pH, organic matter quality and quantity, and site history (Carlyle 1986, Jarvis *et al.* 1996, Purnomo *et al.* 2000). The overall uptake of N by trees is also determined by access to the soil solution through the root system, additional supply from fertiliser, and competitive uptake of N by competing vegetation.

Competition for soil N by herbaceous weeds has been widely reported in plantation forestry particularly during establishment (Ellis *et al.* 1985, Smethurst and Nambiar 1989, Eastham and Rose 1990, Neary *et al.* 1990, Clinton and Mead 1994a, Nilsson *et al.* 1996, Reynolds *et al.* 2000, Robinson *et al.* 2002). Competitive uptake of

nutrients by the weeds occurs at the expense of young trees. This is often attributed to the relatively high root length density (L_v) and therefore large root surface area compared to young trees; the concentration of roots and nutrients in surface soil, and the higher capacity for uptake of N by the weeds during establishment (Nambiar 1990, Hangs *et al.* 2003). Studies have demonstrated that weeds have depleted concentrations of soil N compared to WF conditions, leading to reduced tree growth (Smethurst and Nambiar 1989, Neary *et al.* 1990, Woods *et al.* 1992, Reynolds *et al.* 2000, Robinson *et al.* 2002). For example, in young *P. radiata* plantations on podsolised sand, weeds reduced mineral N by 66 - 80 % (Nambiar and Celliar 1985, Smethurst and Nambiar 1989, Woods *et al.* 1992). In a eucalypt plantation, similar reductions (70 – 84%) during late summer have also been reported (Ellis *et al.* 1985). Reynolds *et al.* (2000) demonstrated that weeds captured N more effectively than young trees, resulting in low availability of nutrients and water, and consequently low growth and physiological activity of the trees.

The effects of forest management such as weed control and N-fertilisation on concentrations of NH_4^+ and NO_3^- in soil solution have been less widely reported, than their concentrations in KCl extracts (Smethurst *et al.* 2001). A useful method for estimating nutrient concentrations in soil solution using saturated paste methodology has been proposed (Smethurst *et al.* 1997). Nutrient concentrations calculated by this method are considered to represent the bulk soil solution, while concentrations at the root surface need further elucidation (Smethurst 2000). When concentrations in soil solution drop, it is expected that concentrations at the root surface also drop, until levels are eventually too low to maintain adequate growth (Moroni 2001). A tentative critical concentration of 0.05 mM for NH_4^+ (and NO_3^-) has been derived for

E. nitens, from mist culture experiments (Sands and Smethurst 1995) and is a level below which strong responses to applied N fertilisers would be expected.

This chapter examines temporal changes in available NH_4^+ , NO_3^- and PO_4^- in soil solution, under contrasting weed, water and N-fertiliser treatments. The main hypothesis tested was that mineral N concentrations in soil solution would be significantly reduced due to grass uptake, reducing N availability to young *E. globulus*, with consequent reductions in tree growth. An additional objective was to determine if, under factorial combinations of irrigation and weed control on a podsolized sand, periodic applications of N-fertiliser would lead to consistently higher N availability, or affect P availability.

7.2 Methods and materials

During the first two years of *E. globulus* growth, concentrations of available N (NH_4^+ and NO_3^-) and PO_4^- were measured in bulk soil solution (0-10 cm depth) using the saturated paste method (Smethurst *et al.* 1997). The KCl method was also used to determine mineral N availability on a subset of data as a comparison to the paste method.

Irrigation (I_{Low} and I_{High}), nitrogen (N_{Zero} and N_{High}) and weed treatments (W and WF) were arranged in a split-plot design in three blocks in Experiment 1 (Table 7.1). Further details are described in Chapter 2 and Chapter 5 for irrigation treatments. Experiment 2 involved five rates of nitrogen fertiliser applied to I_{High} W treatments (Table 7.2). In both experiments the temporal changes in soil nitrogen, phosphorus and other soil and water properties were measured by methods described below.

7.2.1 Irrigation and groundwater chemistry

The irrigation source (channel) was sampled along with groundwater from dip wells (Chapter 5 Figure 5.5a, page 94) across the site over 12 months from October 1997 to August 1998 (tree age 12 – 22 months). The number of samples taken from the channel at each date were $n = 2$, while the number of dip wells providing a sample at each date depended on water presence, but was usually $n = 4$. These water samples were stored frozen (-10°C) until analysis for $\text{pH}_{1.5}$, EC and NH_4^+ , NO_3^- and PO_4^- using Flow Injection Analysis (Lachat Instruments QuikChem 8000).

Table 7.1 Treatments in Experiment 1 (Set 1). Two levels of irrigation, two levels of nitrogen, two periods of weed presence or absence. W = Weedy, WF = Weed-free, 24 = months of duration.

Irrigation	Nitrogen	Weeds
I_{Low}	N_{Zero}	W 24
		WF 24
	N_{High}	W 24
		WF 24
I_{High}	N_{Zero}	W 24
		WF 24
	N_{High}	W 24
		WF 24

Table 7.2 Experiment 2. One irrigation level (I_{High}), one weed treatment (W) and five levels of nitrogen. For the purposes of this study only Oct 1997 and Mar 1998 have been used in the analysis.

Treat No.	Treatment	Nitrogen applied (kg N ha^{-1})		
		Oct 1997	Mar 1998	Oct 1998
1	N_0	0	0	0
2	N_{200}	100	100	50
3	N_{400}	200	200	100
4	N_{800}	400	400	200
5	N_{1200}	600	600	300

7.2.2 Soil properties

Soil samples collected at the site prior to commencing the study were analysed for chemical and physical properties. Soil pH and electrical conductivity (EC) were determined from 1:5 soil/water suspension (Method 4A1 and 3A1 respectively, Rayment and Higginson 1992). Loss on ignition (LOI) was determined by weight loss after heating the soil in a furnace at 375°C for 17 h (Lowther *et al.* 1990). Total carbon content of the sandy horizon was calculated using a regression (Equation 7.1) developed for sandy soils by Lowther *et al.* (1990):

$$\text{Total carbon (\%)} = 0.451 (\text{LOI}) + 0.031 \quad (7.1)$$

($r^2=0.99$)

Total N and P (%) were determined using the automated colour (with > 20 ppm N as nitrate) method 7A4 (Rayment and Higginson 1992. pp 45). Bicarbonate extractable P was determined by the manual colour method 9B1 (Rayment and Higginson 1992. pp 64-66), while exchangeable bases (K^+ , Mg^{2+} , Ca^{2+} and Na^+) were determined by the 1M ammonium chloride (pH 7) method (15A1, Rayment and Higginson 1992). Initial soil properties at the site are presented in Table 7.3.

7.2.3 Soil temperature

Soil temperature was measured using a data logger (CR21x micro-logger, Campbell Scientific Inc. Utah, USA) and copper-constantan thermocouples. The data logger and an air temperature probe were housed at 1.7 m in a Stevenson Screen (Figure 7.1), while the soil thermocouples were placed in a W and WF plot. Measurements were taken at two-hourly intervals for 12 months, from July 1997. For the first six months

temperatures at 7.5 cm depth was recorded (three replicates). After determining no appreciable variation between the three replicates, thermocouples were installed at two further depths (15 and 30 cm) with only one replicate each, for the second six months.

Table 7.3 Initial soil properties

	Soil horizon			
	A1 ⁽¹⁾	Ap	A2	B1
Depth	0-10	0 - 25	25 - 100	100 +
Texture	Sand	Sand	Sand	Sandy clay
Colour ⁽²⁾	10 YR 3/2	10 YR 3/2	10 YR 6/4	7.5 YR 5/8
Bulk density	1.32	1.32	1.55	1.77
pH	6.1	6.1	6.7	7.4
EC dS m ⁻¹	0.37	0.37	0.30	0.89
TKN (%)	0.10	0.07	0.01	0.01
TP (%)	0.02	0.01	0.00	0.00
Available P ⁽³⁾ (mg kg ⁻¹)	32.69	18.66	1.35	0.54
Exch. K (mg kg ⁻¹)	0.13	0.08	0.03	0.14
Exch. Mg (mg kg ⁻¹)	1.18	0.77	0.22	2.26
Exch. Ca (mg kg ⁻¹)	4.16	3.26	1.15	3.90
Exch. Na (mg kg ⁻¹)	0.10	0.06	0.09	1.01
Organic carbon (%)	1.42	0.97	0.23	NM ⁽⁴⁾
C:N ratio	14.2	13.8	23.0	NM
Exch. Bases (mg kg ⁻¹) ⁽⁵⁾	5.57	4.17	1.49	7.31

(1) Surface soil sub-sampled at 0-10 cm depth

(2) Munsell colour chart

(3) Bicarbonate extractable

(4) NM = Not measured

(5) Sum of exchangeable bases



Figure 7.1 Stevenson screen containing data logger for air and soil temperature. Note the unfertilised pale green grass in the foreground.

7.2.4 Fertiliser additions

In Experiment 1, the high nitrogen (N_{High}) treatment involved two applications of urea fertiliser (46% N) in autumn and in spring of each year, providing a total of 900 kg N ha⁻¹ (150, 300, 300 and 150 kg N ha⁻¹) over the two years (Chapter 2, Table 2.3, page 27). Split applications were made to minimise leaching losses and also in an attempt to maintain high levels of fertility over the study period. Application was done to moist soil and was followed by sufficient rainfall or irrigation to minimise volatilisation. The first application (100 kg N ha⁻¹) occurred in April 1997 at age 6 months. The majority was broadcast by hand (75 kg N ha⁻¹) with the remainder (25 kg N ha⁻¹) applied at the same time in a spade slit 20 cm from each *E. globulus* seedling. This was done to ensure that the seedlings in grass treatments had ready access to some nitrogen. A further 50 kg N ha⁻¹ was broadcast during July, three months later.

The next two applications of urea in October 1997 and April 1998 (age 12 and 18 months respectively) were hand broadcast as it was considered that the trees would have sufficiently well established root systems by that stage. In both cases, a higher rate (300 kg N ha^{-1}) was applied as it had become clear that in the initial application (April 1997) the grass had captured a large proportion of the fertiliser. The larger dose was applied in an attempt to improve supply to the young trees. The effective rate in the N_{High} treatment was 750 kg N ha^{-1} . The nil nitrogen (N_{Zero}) treatment received no N fertiliser.

Phosphorus fertiliser (ordinary single super phosphate (9.2 % P) plus trace elements) was applied across the site on three occasions (during grass establishment in August 1996, in December 1996 (tree age 2 months) (broadcast plus spot application) and in June 1998 (age 20 months)). This provided a total of 151 kg P ha^{-1} . Trace elements, particularly copper (Cu) and zinc (Zn) were also supplied because of the risk of induced trace element deficiencies in the sandy soil at this site (Turnbull *et al.* 1994, Dell *et al.* 1995). In spite of these additions, symptoms consistent with Cu and Zn deficiency had appeared in autumn 1998 (age 16 – 18 months), particularly in N_{High} WF treatments. Foliar applications of Cu and Zn were therefore applied ($4.8 \text{ kg Cu ha}^{-1}$ and $5.1 \text{ kg Zn ha}^{-1}$, respectively) in an attempt to alleviate the symptoms. Other nutrients were also applied across all treatments (broadcast and spot application) to provide K (129 kg K ha^{-1}), Mg (16 kg Mg ha^{-1}) and S (183 kg S ha^{-1}) (Table 2.3, Chapter 2).

In Experiment 2, the first nitrogen treatment was applied in October 1997 when the trees were 12 months old. The second and third applications were made in March and October 1998 (18 and 24 months respectively). Other nutrients were supplied as in Experiment 1, with the exception of foliar applications of Cu and Zn. Symptoms indicating deficiency of these two nutrients were not evident on trees in W treatments in Experiment 1 or 2.

7.2.5 Soil solution nutrients

Analysis of soil solution samples was carried out on 10 occasions over the two-year study using the saturated paste method (Smethurst *et al.* 1997). Twelve soil samples (0-10 cm) were randomly collected between the internal four rows of each plot, using a core sampler, then bulked for each plot. Deeper sampling was also done (20 – 40 cm and 50 – 70 cm depth) on one occasion in Experiment 1 in December 1997 (age 14 months) and on two occasions in Experiment 2 in October 1997 and January 1998 (age 12 and 15 months respectively). The fresh soil was stored at 4°C for a maximum of four days before saturated paste analysis. Sub-samples were taken for measurement of soil moisture content, LOI, soil pH (1:5) and EC (1:5).

The paste method uses deionised water, added to fresh soil to produce a saturated paste. The water was added in a ratio of 60:240 (deionised water (ml) to fresh soil (g)) and occasionally 80:240 when the soil was particularly dry. After equilibrating for 1 h, the solution was separated by vacuum filtering through cellulose acetate 0.45 µm membrane. Detection limits for NH_4^+ and NO_3^- were both 0.005 mM and for PO_4^- , 0.1 µM. Non-detectable concentrations were retained in the dataset at one tenth of the detection limit. To convert concentrations in paste extracts to those in

undiluted soil solution, it was assumed that NO_3^- had no interaction with the solid phase and that P was highly buffered. Calculation of NH_4^+ behaviour involved parameters of partition coefficients and the interactive solution of a mass-balance equation (Smethurst *et al.* 1999). The fitted parameters, A and B for a modified Freundlich equation (Smethurst *et al.* 1997) and solid – liquid partition coefficient (K_d) were calculated for soil NH_4^+ concentrations from paste N concentrations.

Initial analyses were carried out using fitted parameters from a clay loam site in northern Tasmania (Nabowla). As this soil did not adequately represent the sandy nature of the Penna soil, fitted parameters were obtained for two sandy soils in Klosterhede (Denmark) and Umeå (Sweden). The mean values for A and B were derived, along with a K_d value. These parameters were subsequently used in analyses (Table 7.4). Phosphorus concentrations were derived using parameters from a sandy soil with low buffer capacity in eastern Victoria (Mendham 1998).

Solutions were frozen (-10°C) until analysis using colorimetric flow injection methods Lachat Quikchem method 12-107-06-1-A for NH_4^+ and method 12-107-04-1-F for NO_3^- . Water was used as the carrier instead of KCl. From age one year (October 1997), cold 2M KCl extracts (Rayment and Higginson 1992) were obtained for analysis of NO_3^- -nitrogen and NH_4^- -nitrogen as a comparison to the soil saturated paste data.

Table 7.4 Fitted parameters A and B, and K_d values used for calculations of initial soil NH_4^+ concentrations using the paste method (Smethurst *et al.* 1997, Smethurst *et al.* 1999), and PO_4^- concentrations (Mendham 1998).

Site	Depth / horizon	Fitted parameters		
		A	B	K_d values at 0.1 mM
NH_4^+				
Nabowla ⁽¹⁾	0 – 10 cm	0.01009	7.2781	3.9
Klosterhede ⁽²⁾	Bhs	0.0293	2.074	1.66
Umeå ⁽³⁾	IICw	0.0386	1.7790	1.22
Mean values used		0.0339	1.9265	1.47
PO_4^-				
Glencoe ⁽⁴⁾		4.97	1.10	6.6

⁽¹⁾ Clay loam (sandstone parent material), pH 5.2

⁽²⁾ Glacial, fluvial sand, pH 4.5

⁽³⁾ Fluvial sand, pH 4.1

⁽⁴⁾ Uniform sand, pH 4.9

7.2.6 Data analysis

Soil characteristics

Soil moisture, pH, EC and organic carbon from Experiment 1 were analysed by ANOVA (Genstat 5 Committee 1994) using a split-plot design with two strata. The term for the irrigation treatment was included in the upper stratum and tested against a residual of two degrees of freedom. The terms for nitrogen and weeds and the interaction were included in the lower stratum and tested against a residual variance with eight degrees of freedom. LSD's were used to determine significant differences between treatments.

Soil solution data was analysed as a split plot design (as above) but also with Date as a split plot factor to investigate Date x Treatment interactions. Three plots were excluded due to grass mortality on the final two assessment dates and were analysed as 'missing data' (Genstat 5 Committee 1994).

Experiment 2 was analysed as a randomised complete-block design, but also included Date as a factor to investigate Date x Treatment interactions.

Soil solution data at the three soil depths (0-10, 20-40 and 50-70 cm) in each experiment were analysed by a two-way ANOVA using Depth and Treatment as the two variables.

Soil temperature

Results are presented as mean monthly and mean weekly temperature (Equation 7.2 and 7.3 respectively).

$$\text{Mean monthly temperature} = (\text{monthly maximum} + \text{monthly minimum}) / 2 \quad (7.2)$$

$$\text{Mean weekly temperature} = (\text{weekly maximum} + \text{weekly minimum}) / 2 \quad (7.3)$$

Mean weekly soil temperature (7.5 cm depth) was regressed on air temperature to determine the relationship for W and WF treatments.

7.3 Results

7.3.1 Effect of weed control

Total mineral N

Three second order interactions were significant ($p < 0.001$). These were Date x Irrigation, Date x N-fertiliser and Date x Weeds. The Date x Irrigation interaction showed that Total N concentrations associated with I_{Low} were higher than for I_{High}

except for the initial two dates (3 and 4 months after planting) and at N-fertiliser applications (12 and 18 months) when concentrations were equivalent (data not presented). The Date x N-fertiliser interaction showed that Total N concentrations under N_{High} were significantly greater than N_{Zero} except during the first 7 months after planting and at the end of the study (24 months) when concentrations were similar (data not presented). The third significant interaction showed that *H. lanatus* significantly reduced the concentration of total mineral N in soil solution (0–10 cm) ($p < 0.001$) between 7 and 18 months after planting *E. globulus*. Concentrations were reduced by approximately 70% (Figure 7.2). Before and after this period reductions were lower and non-significant ($p > 0.05$).

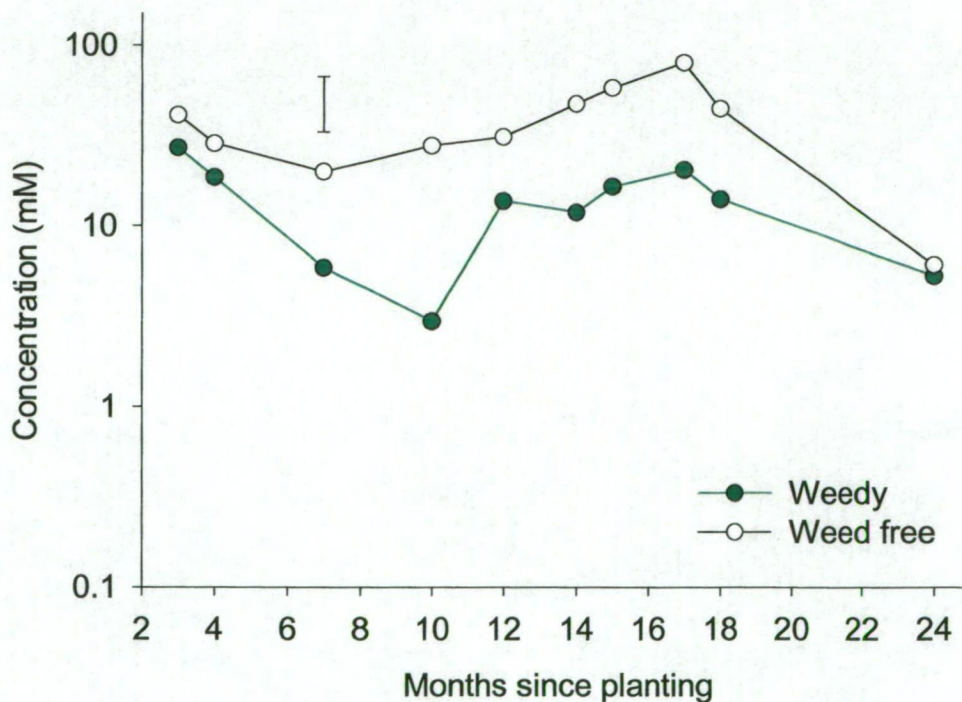


Figure 7.2 Effect of weeds on total mineral N concentrations (across irrigation and fertiliser treatments). Error bar is LSD ($p = 0.05$).

Total mineral N was dominated by NO_3^- (up to 99% of mineral N) across all treatments during most of the study, indicating a strongly nitrifying soil at this site. However, there were periods and treatments, where NH_4^+ constituted up to 49% of mineral N. This was most evident in W treatments following N-fertiliser applications, especially at age 12 months (October 1997).

Ammonium (NH_4^+) (N_{Zero} treatments)

Unfertilised (N_{Zero}) W treatments had higher NH_4^+ concentrations than WF treatments, throughout the two-year study (Figure 7.3 a). Clear seasonal patterns of NH_4^+ concentration were also apparent with high concentrations occurring in spring and summer and low concentrations in winter. Summer concentrations were eight-fold higher than in winter (0.683 mM and 0.082 mM respectively). The level of irrigation also influenced NH_4^+ concentration with the highest concentrations generally occurring in I_{High} W treatment. This is in contrast to I_{High} WF treatments, which had some of the lowest NH_4^+ concentrations. In winter during the first year of growth, NH_4^+ concentrations for all treatments approached the critical concentration (0.05 mM) (Sands and Smethurst 1995) (Figure 7.3 a) with WF treatments being the lowest.

Nitrate (NO_3^-) (N_{Zero} treatments)

Weedy (W) treatments had much lower NO_3^- concentrations than WF treatments throughout the two years (Figure 7.3 b). Nitrate concentrations were higher for I_{Low} WF than I_{High} WF treatments during the first year, but in the second year of growth, were similar between treatments. Seasonal patterns were less apparent for NO_3^- than for NH_4^+ though concentrations were lowest in I_{Low} W (0.39 mM) during late winter

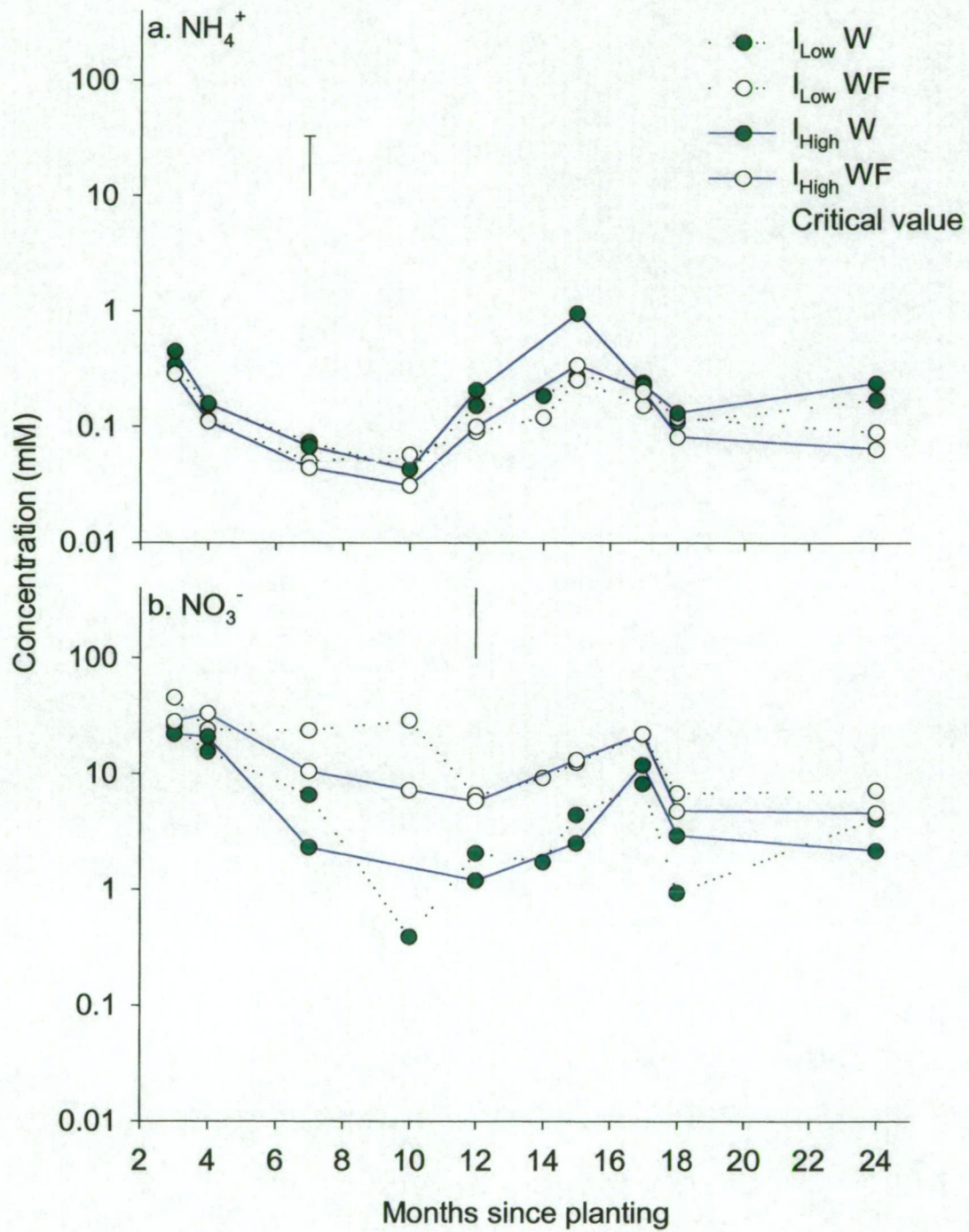


Figure 7.3 Temporal changes in (a) NH_4^+ and (b) NO_3^- concentration to irrigation and weed treatments (unfertilised) in Experiment 1. Error bars are LSD ($p=0.05$).

(Figure 7.3 b). All NO_3^- concentrations were well above the critical concentration (0.05 mM) (Sands and Smethurst 1995).

Phosphate (PO_4^-) (N_{Zero} and N_{High} treatments)

There was a significant Irrigation x Date x N-fertiliser x Weed interaction for PO_4^- concentrations ($p < 0.05$). Up to 15 months after planting, there was a general decline in PO_4^- concentrations before rising back to levels similar to the start of the study by age 24 months (Figure 7.4). At age three months (January 1997) and at 24 months, PO_4^- concentrations were significantly greater than at other times of the study ($p < 0.05$). Phosphate concentrations were generally higher under WF than W treatments during the first year of growth, while in the second year, results were more variable and W treatments were often higher.

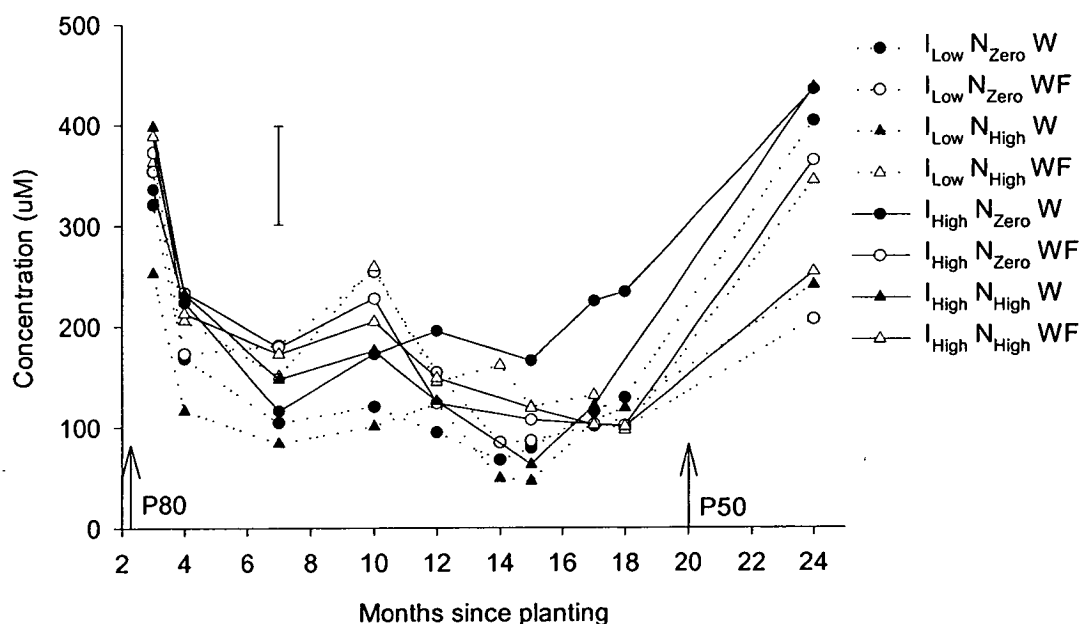


Figure 7.4 Experiment 1. PO_4^- concentration throughout the two year study. Error bar is LSD ($p=0.05$) Arrows indicate P application (kg ha^{-1})

7.3.2 Effect of N-fertilisation

Ammonium (NH_4^+)

There was a significant Irrigation x Date x N-fertiliser x Weed interaction for NH_4^+ concentrations ($p < 0.05$). Following the first N-fertiliser application (age six months) the only treatment to respond immediately was I_{Low} WF (Figure 7.5 b). The I_{Low} W treatments receiving N_{High} responded three months later. At this time (late winter/early spring), NH_4^+ concentrations of all N_{Zero} treatments and I_{High} N_{High} treatments were below 0.05 mM. The second application of N-fertiliser (age 12 months) produced a large increase in NH_4^+ concentrations, in both W and WF treatments (Figure 7.5 a,b). In I_{Low} WF treatments this increase peaked at 9.8 mM, significantly higher than for the first and third N applications ($p < 0.001$) (0.27 and 1.45 mM respectively). Following the high peak, concentrations declined rapidly, and within one month had decreased by over 80%. Another peak occurred following the third N application (age 18 months) (Figure 7.5 a,b). Concentrations in all treatments then decreased towards age 24 months.

Ammonium concentrations in W treatments receiving N_{High} were on average 26% lower than WF treatments between 7 – 18 months, but this was highly variable. This contrasts with N_{Zero} treatments where NH_4^+ concentrations were 55% higher in W than WF treatments.

Nitrate (NO_3^-)

There was a significant Irrigation x Date x N-fertiliser x Weed interaction for NO_3^- concentrations ($p < 0.001$). Nitrate concentrations in WF treatments increased rapidly following application of N-fertiliser, however, I_{High} caused significant reductions in

concentration throughout most of the study (Figure 7.5 cd). In N_{High} W treatments, NO_3^- concentrations were greater than in N_{Zero} W treatments. There was no significant change in concentration due to I_{High} in N_{High} W treatments, though a seasonal trend was apparent. A delay occurred between N-fertiliser application and observed increases in NO_3^- concentration in I_{Low} treatments. In contrast, NO_3^- peaked sooner in I_{High} WF treatments, but subsequently declined to values below W treatments. I_{High} WF treatments peaked again at age 18 months after the third N application (N_{300}). In contrast, concentrations in I_{Low} WF treatments receiving N_{High} gradually increased to give a summer / autumn peak at 235 mM ($p < 0.001$) (Figure 7.5 c). There was no apparent response by the I_{Low} WF treatment to the third fertiliser application (N_{300}) (age 18 months). Concentrations for all treatments decreased from 18 – 24 months (Figure 7.5 d).

Nitrate concentrations in N_{High} treatments were on average 65% lower under grass, compared to WF between age seven and 18 months. Greater reductions occurred in N_{Zero} treatments (74%).

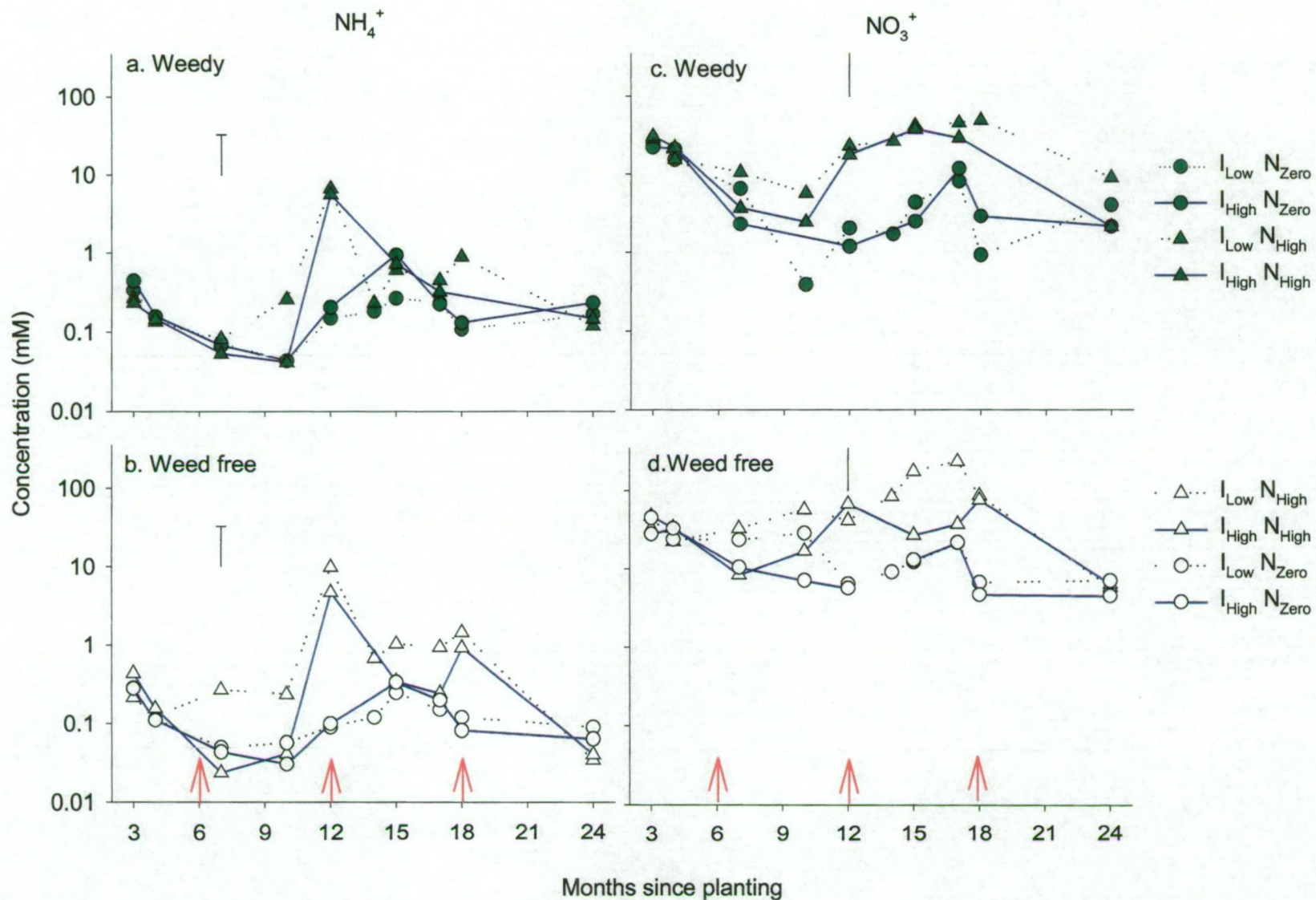


Figure 7.5 Temporal changes in soil solution NH_4^+ concentration (a,b) and NO_3^- (c,d) in surface soil in relation to irrigation, fertiliser and weed treatments. Concentration in log scale. Red arrows indicate N application. Error bars are LSD ($p=0.05$). Broken line indicates tentative critical concentration (Sands and Smethurst 1995).

7.3.3 Rate of N-fertiliser in weedy plots

Ammonium (NH_4^+)

N-fertiliser was applied to W treatments (all I_{High}) in Experiment 2 at age 12 months and 18 months. Prior to this time (late winter 1997) all treatments had concentrations below the critical concentration (0.05 mM) (Figure 7.6 a). There was a significant Date x N-fertiliser rate interaction ($p < 0.001$). Following fertiliser application, NH_4^+ concentrations increased in proportion to N-fertiliser rate. The two highest N-fertiliser rates (N_{400} and N_{600}) produced variable NH_4^+ concentrations, with three peaks at 12, 15 and 18 months. These were significantly greater than the two lowest rates (N_{Zero} and N_{100}) ($p < 0.05$) at age 15 and 18 months. Concentrations in the N_{Zero} treatment peaked at around 18 months then declined along with the other treatments through to age 24 months.

Nitrate (NO_3^-)

There was a significant Date x N-fertiliser rate interaction ($p < 0.001$). Following N-fertiliser application at 12 months, NO_3^- concentrations peaked twice with the second peak larger than the first (Figure 7.6 b). The two highest N-fertiliser rates (N_{400} and N_{600}) had higher peaks, approximately two to three months after the fertiliser application. There was a further peak following the second N application at age 18 months, with significant differences between the highest and lowest N-fertiliser rates ($p < 0.05$). By age 24 months, concentrations of all treatments had declined to levels similar to 20 months earlier (age four months) (Figure 7.6 b).

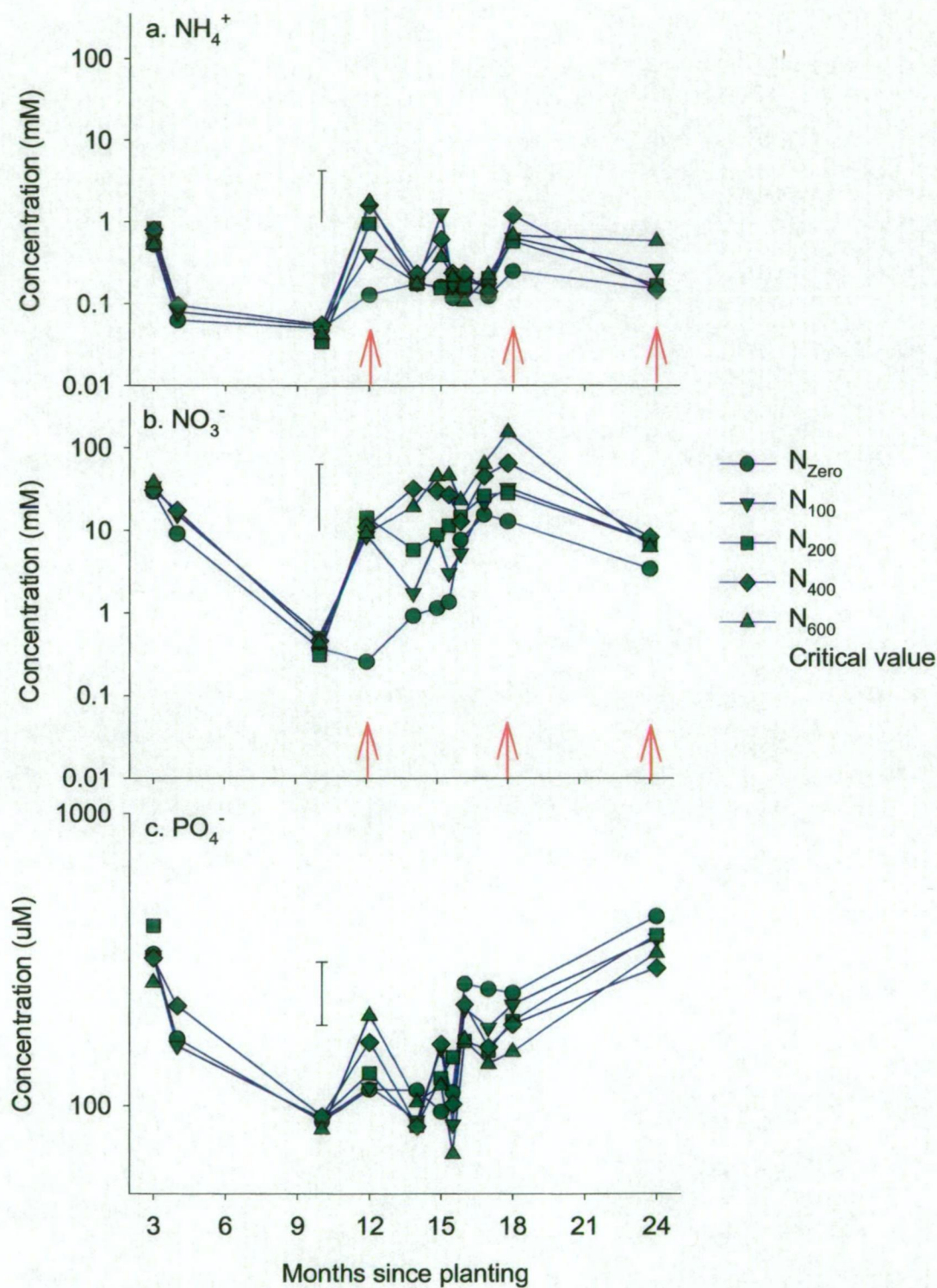


Figure 7.6 Temporal changes in NH_4^+ , NO_3^- and PO_4^- in Experiment 2. All receiving I_{High} W with a range of N fertiliser rates. Note the Log scale for NH_4^+ and NO_3^- . Red arrows indicate N application. Error bars are LSD ($p=0.05$)

Phosphate (PO₄⁻)

Trends in PO₄⁻ concentrations (Figure 7.6 c) were similar to Experiment 1 with a general decline over the first 12 months, followed by increasing concentrations to age 24 months. Significant differences were only found between N treatments at age 18 months ($p < 0.05$) where the highest PO₄⁻ concentrations occurred for the N_{Zero} treatment, and the higher N rates resulted in the lowest P levels. This trend continued through to age 24 months. There was no significant Date x N-fertiliser rate interaction ($p > 0.05$).

7.3.4 Nutrient concentrations by soil depth

There was a significant Depth x Treatment interaction, where concentrations of NH₄⁺, NO₃⁻ and PO₄⁻ declined significantly from the surface (0 – 10 cm) down to 70 cm soil depth (Figure 7.7 a,b,c). Ammonium concentrations were significantly higher ($p < 0.05$) in N_{High} WF treatments than the other treatments at 0 – 10 and 20 – 40 cm depth (0.61 and 0.22 mM respectively). At 50 – 70 cm there were no significant differences between treatments. Although similar results were evident for NO₃⁻, increased concentrations in the N_{High} WF treatment occurred at 20 – 40 cm depth, and were also elevated at 50 – 70 cm compared to other treatments (Figure 7.7 b). In contrast, PO₄⁻ concentrations were significantly higher in N_{Zero} WF treatments ($p < 0.05$) compared to other treatments (Figure 7.7 c) at 0 – 10 cm depth. No significant treatment differences occurred at lower depths.

Results were similar for Experiment 2 with I_{High} W treatments, having significant depth x N-fertiliser rate interactions for NH₄⁺ and NO₃⁻. At age 12 months, higher N

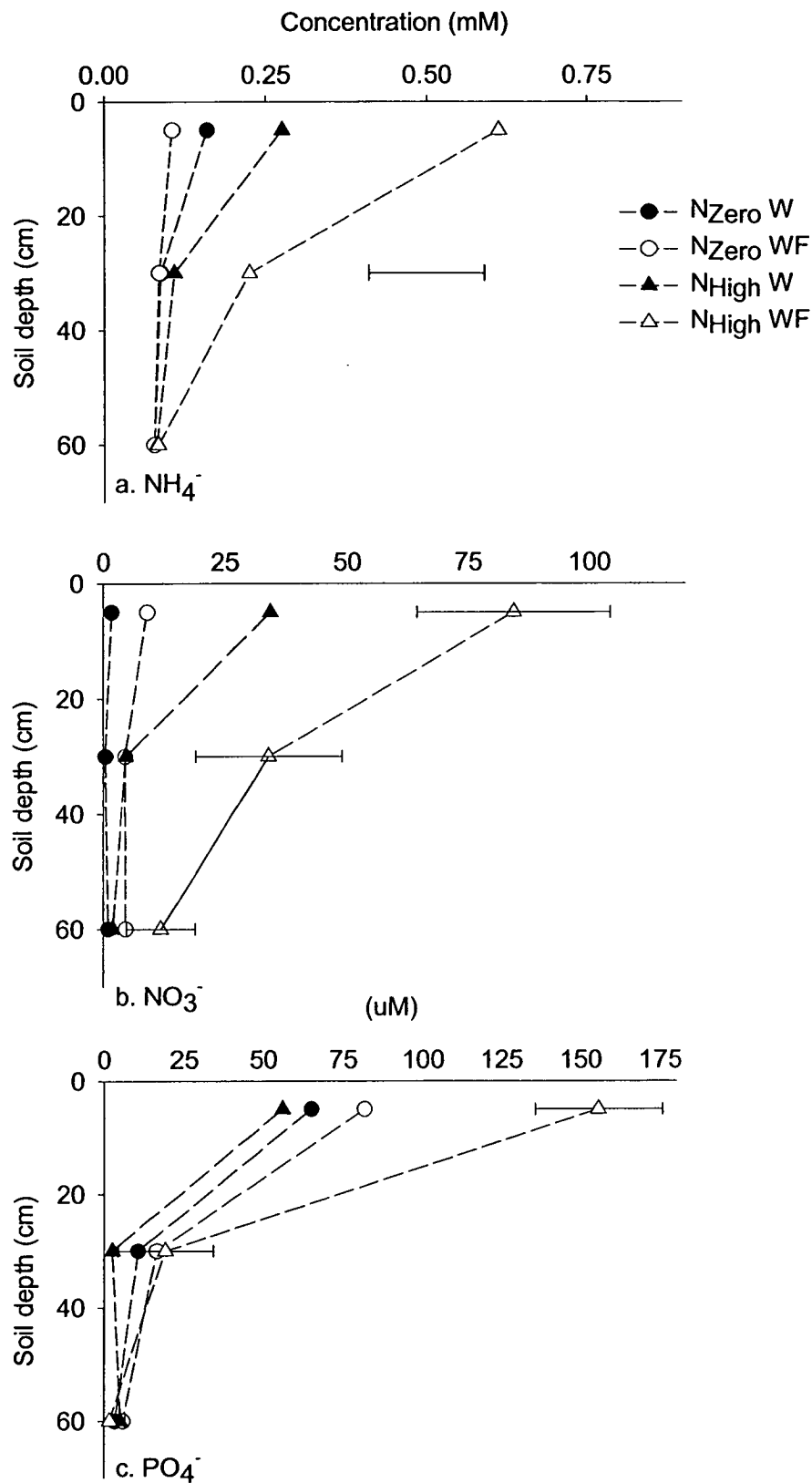


Figure 7.7 NH_4^+ , NO_3^- and PO_4^- concentrations by depth in Experiment 1 (age 14 months). Error bars are LSD ($p=0.05$)

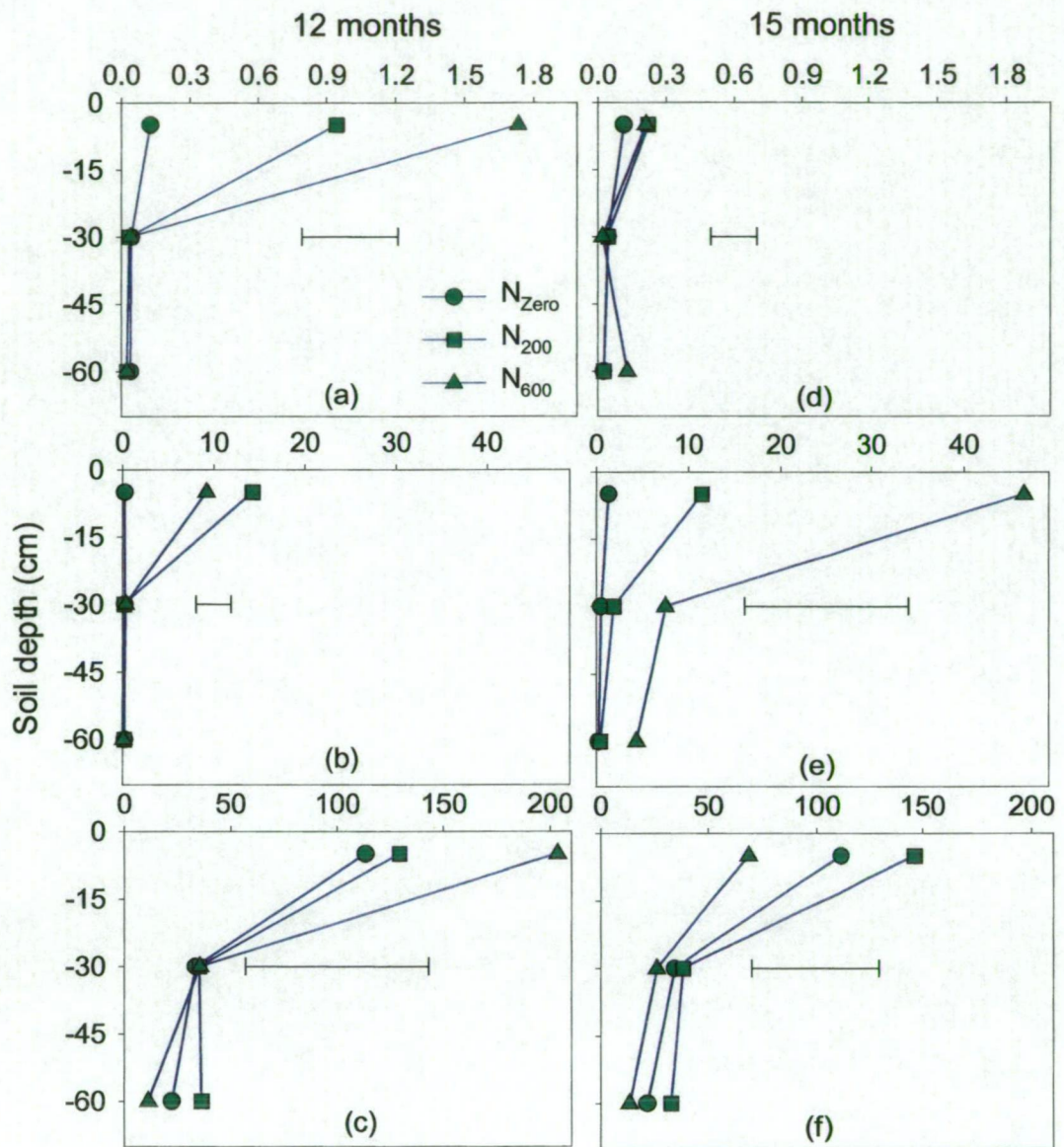


Figure 7.8 NH_4^+ , NO_3^- and PO_4^- concentrations by depth in Experiment 2 (age 12 and 15 months). (a and d) NH_4^+ (mM), (b and e) NO_3^- (mM), (c and f) PO_4^- (uM). Note differences in scale. Error bars are LSD ($p=0.05$).

rates resulted in higher surface concentrations than at depth (NH_4^+ and NO_3^-) (Figure 7.8 a,b). At the highest rate (N_{600}), NH_4^+ concentrations were greatest. In contrast, NO_3^- concentrations for the same treatment were lower than N_{400} in the surface soil. At age 12 months, concentrations of PO_4^- were higher in the surface soil for N_{600}

($p > 0.05$) but at 50 – 70 cm depth, were lower than the other two treatments ($p > 0.05$) (Figure 7.8 c).

At age 15 months (three months after the first sampling date) there was also a significant Depth x N-fertiliser rate interaction where concentrations were higher in the surface soil than lower down. There was no significant difference between NH_4^+ concentrations for each N-fertiliser rate by each depth (Figure 7.8 d). However, NO_3^- concentrations showed large increases for N_{600} since the previous sampling date, increasing from 9 mM to 46 mM, demonstrating a time delay after N-fertiliser application. It was evident that NO_3^- concentrations at the 20 – 40 cm and 50 – 70 cm depth also increased compared to the other treatments (Figure 7.8 e). NO_3^- concentrations in the N_{400} treatment remained similar to those at the previous sampling date. Phosphate concentrations showed that concentrations were significantly higher in the surface than lower down and were lowest for the highest nitrogen rate (N_{600}) at all three depths (Figure 7.8 f), a similar result to Experiment 1.

7.3.5 KCl extractable N

Results from KCl extractable N showed similar trends to the soil solution data (saturated paste method), though absolute and proportional values obtained for NH_4^+ and NO_3^- were different. Conclusions from the limited data set are difficult, however, the KCl data indicated less variability than the paste method (data not shown). In Experiment 1, 14 months after planting, NH_4^+ concentrations were higher in N_{Zero} W treatments compared to N_{Zero} WF (data not shown). The opposite was true for N-fertilised treatments. Both results were consistent with previous findings using the paste method. At age 15 and 17 months, NH_4^+ concentrations were variable with the

I_{Low} N_{High} WF treatments up to 10 fold higher than all other treatments. By the end of the study (24 months) NH_4^+ concentrations had declined in all treatments. However, the W treatments still had higher concentrations compared to WF treatments. Nitrate concentrations were lower under weeds (approximately half), in I_{Low} treatments (N_{Zero} and N_{High}), compared to WF treatments. In I_{High} treatments, NO_3^- concentrations were higher in N_{High} W treatments than in WF treatments (data not shown).

Results from experiment 2 (Figure 7.9 a) showed that NH_4^+ concentrations peaked strongly after each N-fertiliser application, with N_{600} the highest. A sharp decline followed, and no significant differences occurred between treatments until after the second N application (18 months), again with the two highest rates (N_{400} and N_{600}) having the highest concentrations. This second peak was much lower than the first. Nitrate concentrations were more variable due to treatment, with a peak at age 15 months (January 1998) and another at 18 months (April 1998). In general the highest N-fertiliser rates produced the highest NO_3^- concentrations (Figure 7.9 b).

The relationships (log) between KCl - extractable NH_4^+ or NO_3^- and their concentrations in solution was significant for both NO_3^- and NH_4^+ . As there was no effect of treatments on this relationship the data were pooled, resulting in $r^2 = 0.63$ and 0.69 for NO_3^- and NH_4^+ respectively). In Experiment 2 (Figure 7.10), where only the rate of N fertiliser was varied, the relationship was stronger than in Experiment 1 for NO_3^- and weaker for NH_4^+ ($r^2 = 0.86$ and 0.46 respectively). The much greater NH_4^+ levels extracted by KCl compared to the paste method are apparent, and the linear relationship is not as strong as for NO_3^- .

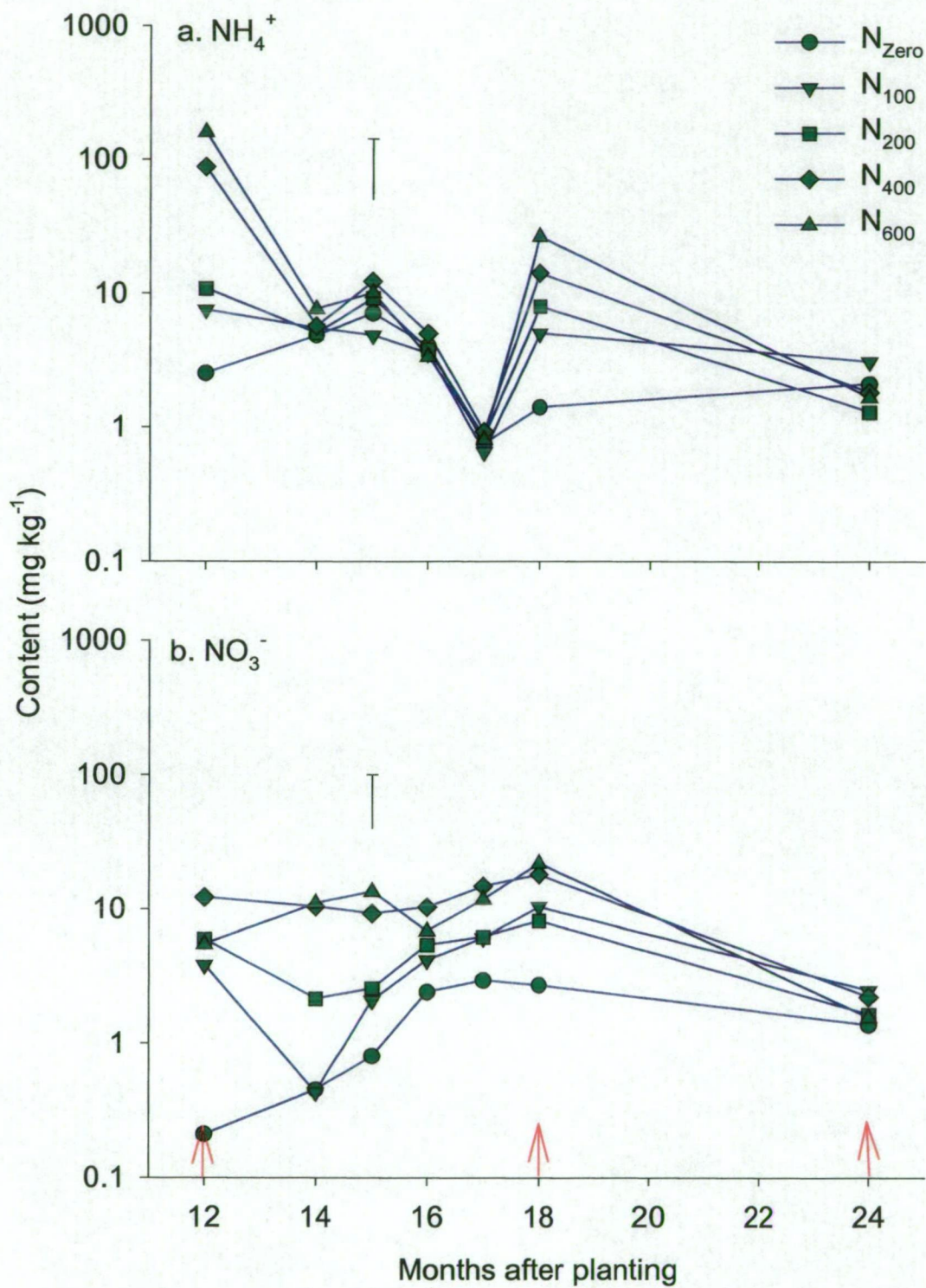


Figure 7.9 KCl – extractable NH_4 and NO_3 during the second year of growth in Experiment 2. Red arrows indicate N application. Error bars are LSD ($p=0.05$)

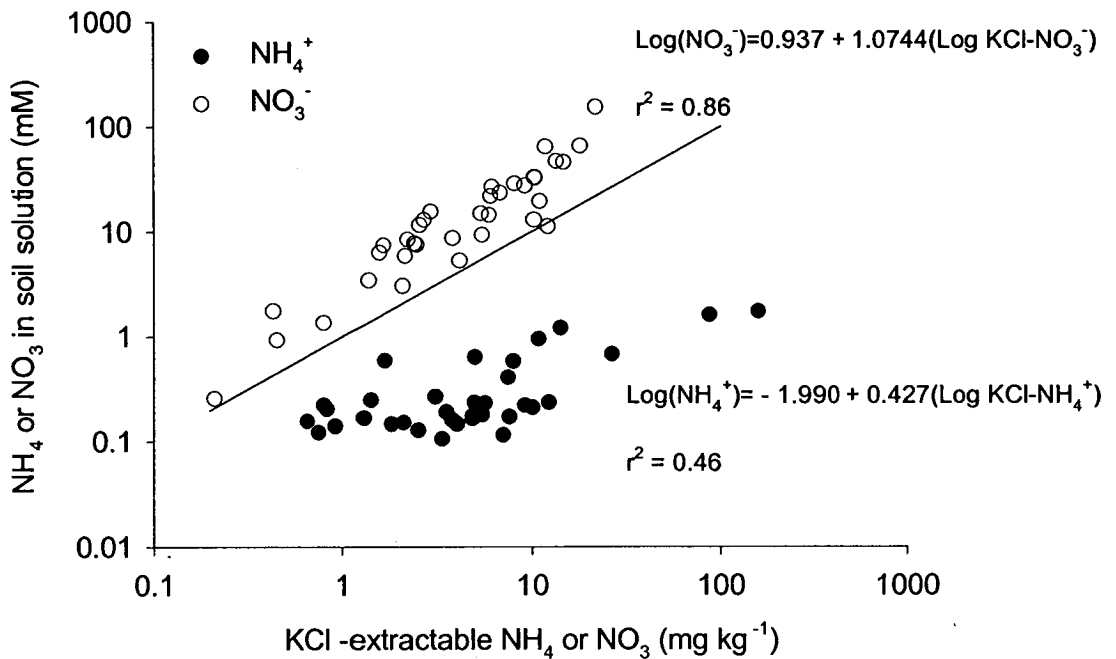


Figure 7.10 Relationships (log) between KCl-extractable NH_4^+ or NO_3^- and their concentrations in solution in Experiment 2. The line indicates the expected relationship if all KCl-extractable mineral-N was in solution (Log_{10} used in equations).

7.3.6 Irrigation water and ground water quality

The pH and electrical conductivity (EC) of irrigation water and groundwater during the second year of tree growth is shown in Figure 7.11. EC was highest in irrigation water during summer ($> 4 \text{ dS m}^{-1}$) but was more moderate during winter ($< 2 \text{ dS m}^{-1}$) (Figure 7.11 a). In contrast, the groundwater EC steadily increased from < 2 to $> 4 \text{ dS m}^{-1}$ during the second year, reflecting the build up of salts due to application of poor quality water. The pH for both irrigation and ground water was more stable, with values of both being around 9 over the same period (Figure 7.11 a). The concentration of nutrients (NH_4^+ , NO_3^- and PO_4^-) in irrigation and groundwater were reasonably stable (Figure 7.12). For both water sources, the concentration of NO_3^-

was much greater than NH_4^+ or PO_4^- , In the groundwater NO_3^- (10 mM) was some 100 times higher than in irrigation water (0 – 1 mM), indicating a large increase of this N species in the groundwater at this site. Ammonium and PO_4^- tended to respond similarly and at equivalent levels, especially in the ground water.

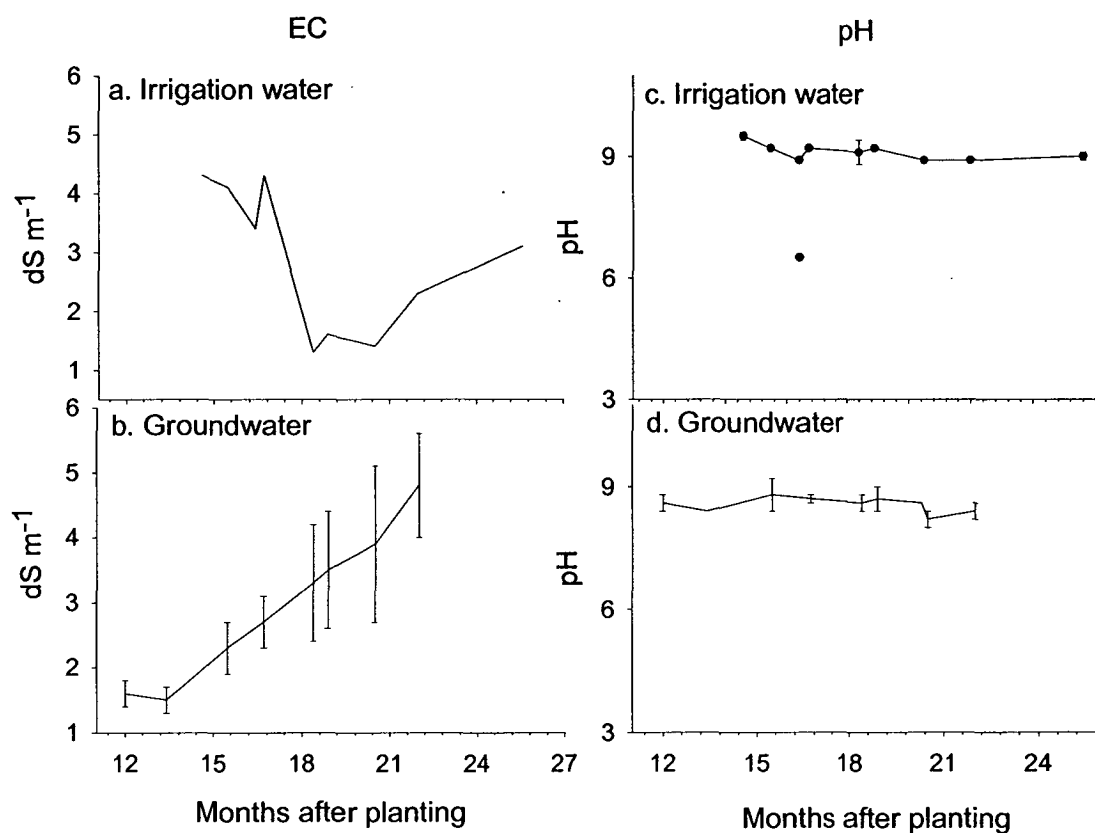


Figure 7.11 Irrigation water EC and pH (a,c) and ground water EC and pH (b,d). Error bars are std dev.

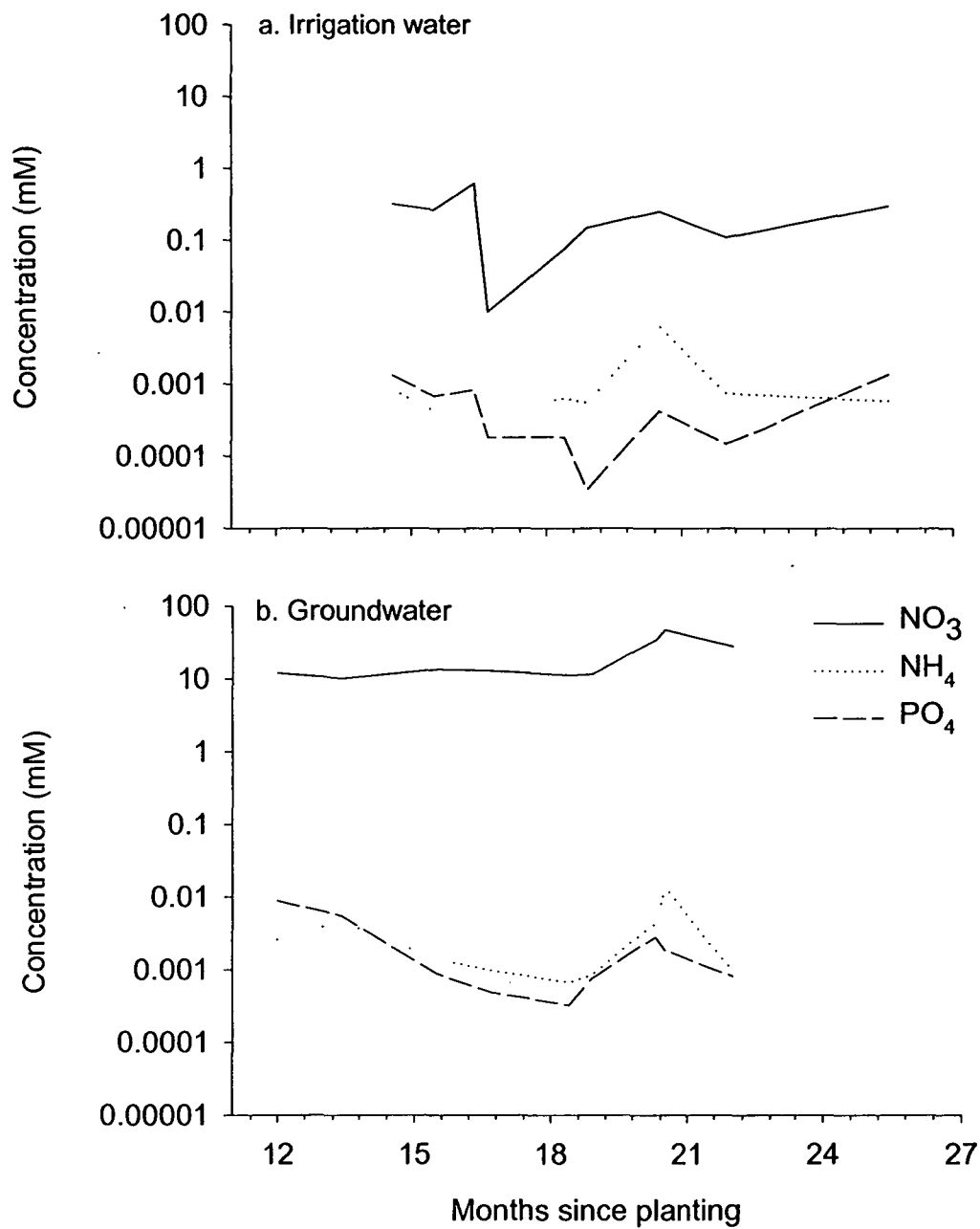


Figure 7.12 Concentration of NH_4^+ , NO_3^- and PO_4^{3-} (mM) in irrigation and groundwater during the second year of growth.

7.3.7 Other soil factors

pH

Soil pH (0-10 cm) generally increased during the study (Figure 7.13). There was a water by nitrogen interaction apparent 12 months after planting when pH of both I_{High} and $I_{\text{Low}} N_{\text{Zero}}$ increased by over 1 unit (pH 6.1 to 7.2) ($p < 0.05$). In contrast, pH in $I_{\text{Low}} N_{\text{High}}$ had not changed from the original level. These effects were maintained throughout the second year of growth, except in treatment $I_{\text{Low}} N_{\text{Zero}}$, which decreased below pH 7 towards the end of the study (Figure 7.13).

Salinity

Salinity levels (EC dS m^{-1}) varied in the surface soil but remained moderate throughout the study (data not shown). Three months after planting, the mean level was 0.25 dS m^{-1} with no significant difference between treatments. However, by spring (age 12 months), salinity levels had decreased with a significant water by nitrogen by weeds interaction ($p = 0.014$) (data not shown). Where N-fertiliser was applied, $I_{\text{Low}} W$ had the highest EC (0.19 dS m^{-1}) while in unfertilised treatments $I_{\text{Low}} WF$ had the highest EC (0.13 dS m^{-1}). In summer (age 15 months), salinity levels increased to 0.33 dS m^{-1} reflecting the poorer quality irrigation water available during this period. In winter, following water recharge, EC had again declined to lower levels (0.12 dS m^{-1}).

Organic carbon

Surface soil organic carbon was 1.13% across the site and did not vary significantly during the two-year study. This value is equivalent to a total soil carbon content of 14.9 t ha^{-1} (0-10 cm depth).

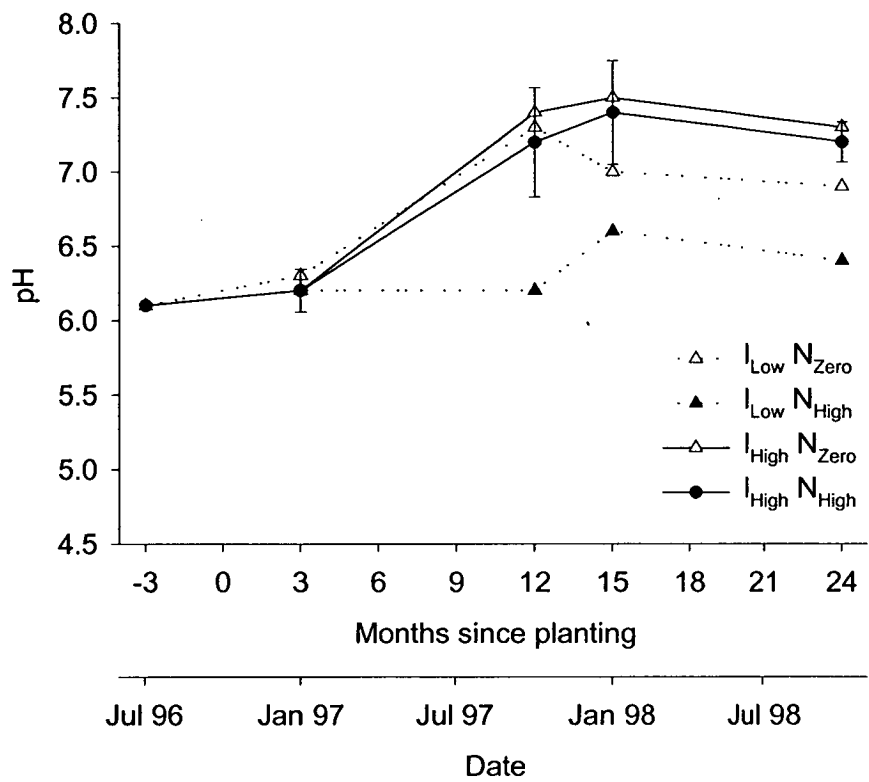


Figure 7.13 Experiment 1. Soil pH (0-10 cm) changes over two years under irrigation, nitrogen fertiliser and weed treatments. Error bars are LSD ($p=0.05$).

7.3.8 Soil temperature

Air and soil temperature data showed the characteristic unimodal relationship with high summer and low winter temperatures (Figure 7.14). Soil temperature at 7.5 cm depth in the W treatment closely followed air temperature. In summer, soil temperature was higher (3 – 4°C) in WF than W treatments; in winter it was slightly cooler (-1°C) in WF than W. The period when soil temperatures were warmer in WF treatments than W treatments was from September to April. These differences were also present at 15 and 30 cm depth (Table 7.5).

Table 7.5 Mean monthly air and soil temperature (°C) by depth (7.5, 15 and 30 cm)

Month	Air	Depth 7.5 cm		Depth 15 cm		Depth 30 cm	
		W	WF	W	WF	W	WF
Jul	8.3	8.2	7.8				
Aug	8.9	8.5	8.7				
Sep	9.6	10.1	11.4				
Oct	11.9	11.6	14.7				
Nov	14.1	13.8	17.8				
Dec	14.6	15.4	19.2	15.5	20.1	15.0	19.4
Jan	17.5	18.1	22.5	17.6	22.3	17.1	21.6
Feb	16.6	17.1	20.3	17.0	20.2	16.9	19.9
Mar	15.1	15.1	18.1	15.3	18.1	15.4	18.1
Apr	12.3	12.8	13.5	13.1	13.8	13.5	14.3
May	10.1	10.8	10.5	11.0	10.8	11.5	11.4
Jun	7.7	8.8	7.8	9.1	8.3	9.7	9.0

Soil temperature was related to air temperature (Figure 7.15) in both treatments but with significantly different slopes and intercepts ($p < 0.05$). The larger the air temperature the larger the soil temperature difference between W and WF treatments, For air temperatures $< 9^{\circ}\text{C}$, corresponding with early spring and early autumn, soil temperatures in W were greater than WF treatment, while the converse was true for air temperatures $> 9^{\circ}\text{C}$ (Figure 7.15).

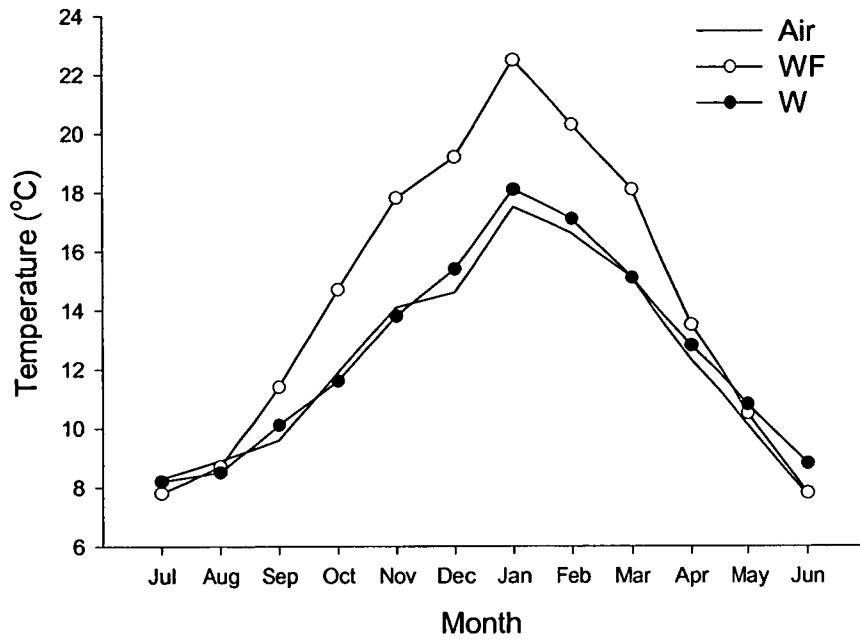


Figure 7.14 Mean monthly air and soil temperature (7.5 cm depth) for WF and W from July 1997 to June 1998

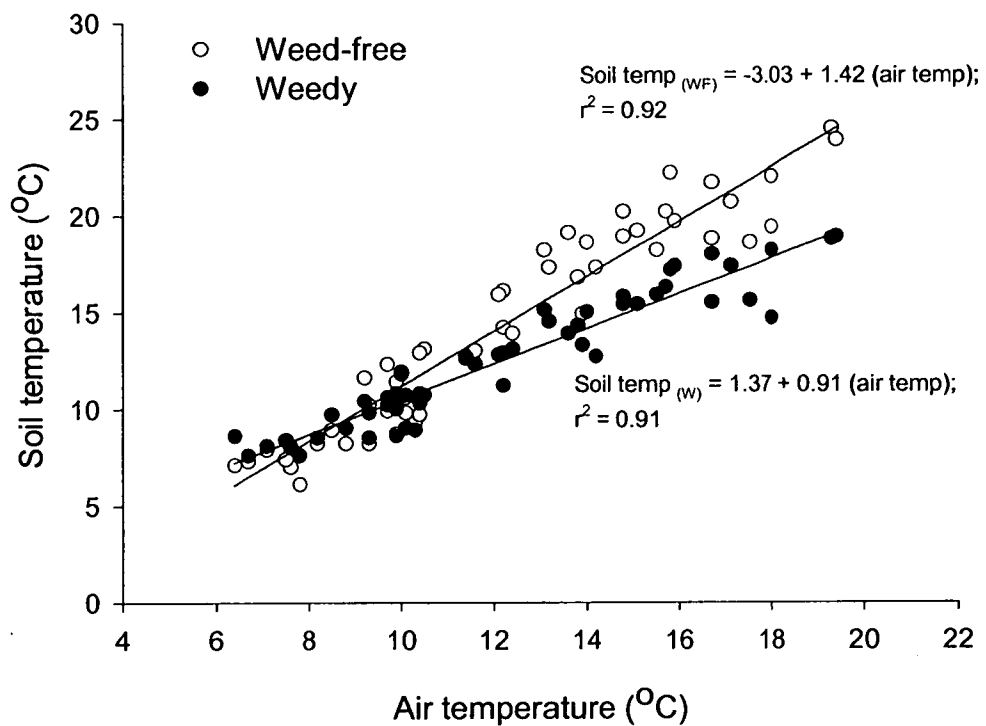


Figure 7.15 Regression of soil temperature on mean weekly air temperature (7.5 cm depth) for W and WF.

7.4 Discussion

Total mineral N (NH_4^+ and NO_3^-) in soil solution significantly decreased in the presence of *H. lanatus*, with reductions of up to 70% during the first 18 months of *E. globulus* growth. Other studies investigating mineral N changes have shown similar levels of depletion (Ellis *et al.* 1985, Nambiar and Celliar 1985, Smethurst and Nambiar 1989, Neary *et al.* 1990, Woods *et al.* 1992, Nilsson *et al.* 1996, Thevathasan *et al.* 2000). For example, two studies in young *P. radiata* plantations, showed that herbaceous weeds (including *H. lanatus*) reduced mineral N concentrations by 66 - 80 % in the soil surface (Nambiar and Celliar 1985, Smethurst and Nambiar 1989). In a similar study and location, where N-fertiliser was applied, weeds reduced mineral N by 50 % in comparison to WF treatments (Woods *et al.* 1992). And in a high altitude *E. delegatensis* plantation, native grasses (*Poa* spp.) reduced total mineral N by 70 – 84% during late summer (Ellis *et al.* 1985). The high capacity of grass to deplete mineral N has also been demonstrated in many agricultural studies (Whitehead 1995, Jarvis *et al.* 1996)

Mineralisation and nitrification were not measured directly in this study, however, concentrations of NH_4^+ and NO_3^- in soil solution indicated that supply rates into solution were relatively high and followed a seasonal pattern with a summer high and winter low. In unfertilised plots, NH_4^+ concentrations were higher under W than WF treatments, and were enhanced by increased soil moisture content (high irrigation) which probably increased nitrogen mineralisation rates. Higher organic matter content and a relatively high nitrogen content, enhance mineralisation rates (Handreck and Black 1991, Whitehead 1995, Moroni 2001). Spatial patterns of

mineralisation show its close association with soil organic matter, with highest rates occurring in the surface soils (Smethurst and Nambiar 1989, Xu *et al.* 1996, Tang *et al.* 2000, Purnomo *et al.* 2000). However, subsoil can also contribute a significant portion of the N supply (Carlyle 1986). In the current study, there was no significant increase in organic matter with time, even though there was very high above-ground grass biomass (up to 14 t ha⁻¹). The reason for this is not clear and contrasts with other weed studies where significant increases in organic matter have occurred, along with increased rates of mineralisation (Atkinson 1977, Vitousek *et al.* 1982, Nilsson *et al.* 1996, Reynolds *et al.* 2000). Woods *et al.* (1992) reported that topsoil organic matter increased by 3.9 t ha⁻¹ and N mineralisation rates increased due to the presence of grass in a young *P. radiata* plantation. However, at a site with low weed biomass (2 t ha⁻¹), organic matter levels did not increase (Smethurst and Nambiar 1989).

The site had high availability of mineral N initially, but this was depleted in the presence of weeds such that mineral N availability became limiting to trees within five months, with many young *E. globulus* displaying symptoms of N deficiency from this time onwards. The lowest NH₄⁺ concentrations occurred during the first winter after planting (age 6 – 10 months) when they approached 0.05 mM, the proposed critical value (Sands and Smethurst 1995). It was after this period that *E. globulus* growth responses occurred in W treatments when N-fertiliser was applied. Similar responses have been observed after soil solution NH₄⁺ and NO₃⁻ concentrations declined below 0.05 mM in a two- to three-year-old *E. nitens* plantation (Smethurst 2000).

Nitrate concentrations under weeds were much lower compared to WF treatments. This suggested the strong NO_3^- uptake rates by the grass. High N uptake rates by grasses have been well documented and under favourable conditions, uptake rates can be more than $500 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (Whitehead 1995). Grass in a two- to three-year old *P. radiata* plantation took up $69 - 171 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (Woods *et al.* 1992), while Neary *et al.* (1990) reported $55 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ by grass in a young *P. taeda* plantation. In another study, the N uptake rate by pasture species, including *H. lanatus*, in a one-year-old *P. radiata* plantation was 389 kg N ha^{-1} (Parfitt *et al.* 2003). In a root study by Hangs *et al.* (2003), NH_4^+ and NO_3^- uptake rates have been quantitatively described for several boreal forest species, including a competitive grass (*Calamagrostis canadensis* (Michx.) Beauv). Results showed that in comparison to white spruce (*Picea glauca* (Moench.) Voss) and jack pine (*Pinus banksiana* Lamb.), *C. canadensis* had a much higher demand for both NH_4^+ and NO_3^- , and a very efficient uptake system, with the ability to rapidly deplete mineral N from soil solution. In contrast, both tree species had a limited capacity to uptake NO_3^- , even after NH_4^+ had been depleted (Hangs *et al.* 2003).

Phosphate concentrations were largely unaffected by grass presence, with concentrations in most treatments behaving similarly (see also Nambiar and Celliar 1985). There appeared to be an adequate supply of P for both grass and trees. However, there was a non-significant trend for higher PO_4^- concentrations in WF than W treatments during the first year of growth. By the second year it was evident that concentrations under N-fertilised grass were lower than other treatments. This was probably due to greater uptake promoted by increased grass growth. A similar

effect was evident in experiment 2 in W treatments receiving the highest N-fertiliser rate (N_{600}) and down to 60 cm soil depth.

Seasonal patterns of mineralisation are related to soil moisture and temperature and it is generally expected that rates of mineralisation will decrease as soil water content decreases (Theodorou and Bowen 1993, Prasolova *et al.* 2000) and will increase as soil temperature increases (Adams and Attiwill 1986b). In this study, mineralisation rate was probably temperature and moisture driven because maximum concentrations occurred in summer and minimum concentrations in winter. In the seasonally dry climate of south-western Australia on sandy soils, mineralisation rates were highest during late winter and spring (favourable water and temperature regime) and lowest in summer and early autumn when surface soils dried below wilting point (O'Connell and Rance 1999). In contrast, on fertile clay loams in reliable summer rainfall areas, seasonal patterns were less evident, while on other sites, rate of mineralisation was mainly attributed to concentrations of mineralisable substrate (Wang *et al.* 1998, Moroni 2001).

In the current study, the amount of organic N in topsoil (0-10 cm) was estimated to be approximately 1.3 tonnes N ha⁻¹. Rates of mineralisation in this relatively infertile sandy soil would have been in the order of 1 – 2 % total organic N. Such levels have been observed by Cole (1995) in temperate forest soils and Connell *et al.* (1995) in a range of soils in south-eastern Australia. At this site, mineralisation would therefore be approximately 13 – 26 kg N ha⁻¹ yr⁻¹, a relatively low rate. This is consistent with low rates in similar podsolised sandy soils (Smethurst and Nambiar 1989, Woods *et al.* 1992, Carlyle *et al.* 1998, O'Connell and Rance 1999). However, moderately high

mineralisation rates ($70 - 100^+ \text{ kg N ha}^{-1} \text{ yr}^{-1}$) can also occur in these soil types. A similar range of mineralisation rates has been reported for clay loam soils in *E. nitens* plantations (Wang *et al.* 1998). On ex-pasture sites, mineralisation rates are usually high due to high fertiliser use and a legume component (Skinner and Attiwill 1981, Birk 1994) but may also be related to the quality of organic matter (Moroni 2001). In a study comparing mineralisation rates between pasture and WF treatments in a young *P. radiata* plantation, Parfitt *et al.* (2003) found that N mineralisation rates were 325 kg N ha^{-1} under pasture during the first year of growth.

The mineral N dominance of NO_3^- , as measured by the paste method, indicates the strong nitrifying nature of the soil at this site, that resulted in rapid nitrification of NH_4^+ to NO_3^- and very low soil solution $\text{NH}_4^+ : \text{NO}_3^-$ ratios (ca. 1:100). High nitrification rates are common in ex-pasture soils (Whitehead 1995, Parfitt *et al.* 2003) and are also enhanced by high soil pH (McLaren and Cameron 1997). These conditions may also have stimulated NO_3^- uptake by *H. lanatus* (Steele 1980). In WF treatments however, the high availability of NO_3^- would have been due to the ready nitrification of the NH_4^+ , lowered microbial demand for mineral N because of lower quantities of C substrate (Parfitt *et al.* 2003), higher soil temperatures, and a lack of uptake by grass. As a result, enhanced NO_3^- was susceptible to losses through leaching, and this was indicated in I_{High} treatments in WF treatments. The high NO_3^- concentrations in these treatments did not approach the critical concentration (0.05 mM) (Sands and Smethurst 1995).

The application of N-fertiliser rapidly increased the availability of mineral N in soil solution but these were only short-lived. The return to pre-fertilisation

concentrations, soon after fertilising is common and reflects the dynamic nature of nutrients in soil solution (Fisher and Binkley 2000) and susceptibility to losses through leaching. Long-term availability of mineral N was not improved by N-fertiliser, even at the high rates applied (up to 900 kg N ha⁻¹) and by the end of the study, NH₄⁺ and NO₃⁻ concentrations were as low or lower than at the start. This demonstrates the difficulty of maintaining stable soil solution concentrations, in a sandy soil with low buffering capacity, seasonal changes in soil water content and temperature, leaching, and plant uptake. It also indicates that N-fertilisation increases productivity of the weeds and trees rather than long-term site productivity (Miller 1981).

The importance of water for nutrient transport and uptake by roots is widely recognised (Berkowitz 1988, Nambiar 1990, Goncalves *et al.* 1997, Tinker and Nye 2000) and with the restricted tree root systems in weedy treatments, would have been particularly important in this study. This was highlighted when *E. globulus* growing in W treatments, appeared to respond more strongly to spring N-fertiliser application, when high irrigation was also applied (Chapter 4). This was despite being unable to demonstrate higher water content in surface soil due to this treatment (Chapter 5) and the fact that lower mineral N concentrations occurred in this treatment compared to those with low irrigation. Several studies have demonstrated tree growth responses to applied nitrogen in the presence of weeds, particularly where water is not limiting growth (Neary *et al.* 1990, Woods *et al.* 1992); or when irrigation has been used to reduce competition for water (Goode and Hyrycz 1976, Richardson *et al.* 1993).

A major effect of high irrigation was increased leaching of mineral N from the surface soil. High leaching losses can occur, particularly for NO_3^- where mobility is strongly controlled by water (Tang *et al.* 2000). This was reflected in relatively high NO_3^- concentrations at 20 – 40 cm and 50 – 70 cm depth in December and January for experiment 1 and 2 respectively. The decreasing NH_4^+ concentrations with I_{High} suggests that it was also leached, due to the low cation exchange capacity of the sand and low organic matter content. Smethurst and Nambiar (1989) report that NH_4^+ constituted 30% and 45% of the N leached in WF and W treatments respectively in a podsolised sand, and that three times higher mineral N leached below 30 cm in WF treatments compared to W (between 9 and 15 months after planting). In the present study, NH_4^+ concentrations in treatments receiving I_{High} declined by 62% (0 – 10 cm) in WF conditions, and by 18% in the W treatments. Increased nitrification would also have been promoted by higher water availability.

Denitrification, where NO_3^- is converted to NO_2^- and lost as gas, is another major potential loss of mineral N (Davidson 1990). Although high soil pH at this site would have favoured denitrification, the process would have been limited by the low soil water content and high aeration of the sandy surface soil (Tiedje 1982). However, denitrification may have been more important in the subsoil, where high water content and anaerobic conditions (Pell *et al.* 1996) occurred periodically.

Volatilisation is another process whereby mineral N losses can occur and is commonly associated with the use of urea fertiliser (M^cLaren and Cameron 1997). In this study, cool weather was followed by irrigation soon after each N-fertiliser application, which would have minimised losses from this process.

Analysis of soil solution N via the saturated paste method (Smethurst *et al.* 1997) provided insight into the effect of weeds on mineral N availability for young *E. globulus* growth. It has been useful for identifying nutrient limitations even if it could not represent the quantities of available nutrients throughout the year. It reflects the concentrations likely to occur in bulk soil solution (Smethurst 2000) and provides an indication of the mobility of nutrients to roots and also potential for leaching (Barber 1984, Marschner 1995). Smethurst *et al.* (2001) found that concentrations of NH_4^+ and NO_3^- in soil solution have been stable enough to clearly observe fertility trends, and showed that NH_4^+ concentrations near the critical value provided an indication of nitrogen deficiency in a *E. nitens* plantation. *E. globulus* responses to N-fertiliser under weedy conditions suggests that the critical value for NO_3^- may be much higher than for weed-free conditions. Estimation from Figure 7.5 c, indicates that the concentration in bulk soil solution may be closer to 3 – 4 mM. This is because Sands and Smethurst (1995) used a hydroponic system (mist culture experiments) for determination of the 0.05 mM critical concentration, so there would have been good solution contact with the tree root systems. However, under field conditions, root depletion zones change with soil moisture content and the depletion zone around an individual *E. globulus* root would have had a much lower concentration than in bulk soil solution.

Results from KCl extractable N are in agreement with soil solution results from the paste method. However, it is apparent that the paste method has been more sensitive to concentration variation at the low end of the range. The high $\text{NH}_4^+:\text{NO}_3^-$ (1:100) ratio compared to that derived from KCl data (closer to 1:1), is related to higher NH_4^+ extraction by the KCl method. High rates of nitrification were also indicated.

The high correlations for extracted NO_3^- achieved between the two methods were expected, with a slope close to one, due to an expected negligible interaction between NO_3^- and the soil (Black and Waring 1976). However, correlations with NH_4^+ were not expected to be 1:1, due to interactions with NH_4^+ and cation exchange surfaces and the greater detection of NH_4^+ by the KCl method. Correlations reported by Moroni (2001), were not as good as those determined from Experiment 2 in this study ($r^2 = 0.3$ and 0.43 for NH_4^+ and NO_3^- respectively).

The importance of grass presence on microclimatic factors such as soil temperature was demonstrated in this study, with substantially reduced surface soil temperatures, and delayed warming in spring / summer, compared to WF treatments. Weekly soil temperatures (7.5 cm depth) during summer, were 5°C lower in W compared to WF treatments, while in winter the grass provided an insulation effect with soil temperatures 1°C higher than WF. Similar findings have been reported in a clay soil by Leeper (1967). Trees growing in WF treatments had warmer soil temperatures during the growing season than in W treatments which would have enhanced root growth, microbial activity and N-mineralisation (Leeper 1967, Adams and Attiwill 1986a, Whitehead 1995, Caldwell *et al.* 1995, Nilsson *et al.* 1996, Reynolds *et al.* 2000). Weed-free treatments also warmed up earlier in spring than W treatments leading to faster early growth at the start of the growing season. In winter, the soil temperature in both W and WF treatments were $<10^\circ\text{C}$, which would probably limit rates of mineralisation and nitrification as well as root growth (Ellis 1974, Nadelhoffer *et al.* 1991).

The rate of leaf area development in young trees is strongly influenced by the amount of available light. In this study the presence of grass appeared to reduce the amount of reflected light compared to bare soil within the plantation, especially during the first year of tree growth. A measure of this can be determined by the reflection coefficient (albedo), which is measure of the average reflectivity over a specific waveband, weighted by the distribution of radiation in the solar spectrum (Monteith 1973). Reflection coefficients have been calculated (Monteith 1973), and for bare soil, have been shown to depend on the soil organic matter content, wetness, particle size and angle of light incidence for bare soil. For grass cover, the reflection coefficient depends mainly on the angle of light incidence. The difference in coefficients between bare soil and grass may be an important factor contributing to the faster early growth and leaf area development of the young seedlings in WF compared to W treatments. However, data reported in Monteith (1973) shows that sandy soil and grass or pasture coefficients are very similar (25 – 30%). Therefore, this is an area that requires further investigation.

Over-topping by the grass and direct competition for light was not present in this study because timely and effective slashing around *E. globulus* seedlings was carried out. Another effect on microclimate is the impact on air temperature above the soil surface and is also influenced by grass presence (Simard *et al.* 2003), with direct impacts on the growth and development of the young trees.

7.5 Conclusions

The results from this study support the hypothesis that grass competition by direct mineral N uptake has been a major factor in the interaction between grass and young *E. globulus* from an early age and continuing beyond age two years. *H. lanatus* had a high capacity for mineral N uptake, depleting the total mineral N by up to 70 % during the first 18 months of tree growth, which resulted in lower availability of mineral N for uptake by *E. globulus*. The low mineral N availability was further exacerbated by the restricted root systems of the young trees compared to the high root length density of the grass.

Mineral N depletion was greatest during spring (age 12 months) when both trees and weeds had a high growth potential. The differences in behaviour between NH_4^+ and NO_3^- in response to weed, fertiliser and irrigation treatments reflected their differences in transformation, mobility and the influence of the low buffering capacity of the sandy soil, seasonal changes in soil water and temperature, leaching, and plant uptake. An indirect effect of N-fertiliser application in W treatments was the reduced PO_4^- concentrations in soil solution, due to the higher uptake rates by the vigorous grass.

The timing and rate of fertiliser and irrigation had a strong impact on supply, availability and losses of mineral N from the grass – *E. globulus* system. Rapid increases in mineral N occurred following N-fertiliser application, however they also subsequently declined rapidly, due to the low buffer capacity of the soil and uptake by weeds. When high irrigation was applied in conjunction with N-fertiliser, the

growth response by *E. globulus* to increased mineral N availability was enhanced, indicating the importance of soil water for uptake and mineralisation.

In WF treatments, the increased mineral N concentrations exceeded *E. globulus* requirements, and high nitrification rates on this ex-pasture site, resulted in high leaching losses of NO_3^- . However, in W treatments, the increased NH_4^+ and NO_3^- concentrations were rapidly captured by the grass, which also reduced leaching losses.

Depleted mineral N due to grass presence provides strong evidence that competition for this resource has occurred. Further evidence will now be sought on the uptake of mineral N and P by *H. lanatus* and *E. globulus*, to improve understanding of the timing, duration and importance of competition for these resources. This is examined in Chapter 8.

8. Influence of *H. lanatus* on foliar nutrient status of *E. globulus*

8.1 Introduction

Plant nutrient status is a critical determinant of tree health and productivity (Haase and Rose 1995). Often, poor tree growth can be associated with declining levels of plant nutrition expressed as lower foliar nutrient concentrations or contents (Marschner 1995). Where weeds are present in young plantations, competition for nutrients can reduce nutrient uptake by trees and lead to lower levels of foliar nutrition (Caldwell *et al.* 1995, Nilsson *et al.* 1996).

The use of foliar analysis for determining foliar health and status has been successfully applied for many tree species, particularly conifers (Fischer and Binkley 2000), that have determinant growth with single growth flushes each year. Good relationships have been established between foliar nutrient concentration and future growth (Richards and Bevege 1972). Yield response curves (Bates 1971) are well established for many species, and are widely used for *P. radiata* in New Zealand and Australia (Raupach 1967, Will 1985).

Eucalypts have an indeterminant growth habit, often with leaf size differences within an individual, and may have multiple growth flushes during a twelve-month period (Jacobs 1955). Therefore, the relationships between foliar nutrient concentrations and changes in eucalypt growth rate or productivity can be poor. Some species of eucalypts maintain a steady nutrient concentration during periods of reducing growth rate (Shedley *et al.* 1995). Low foliar nutrient concentrations can often be explained

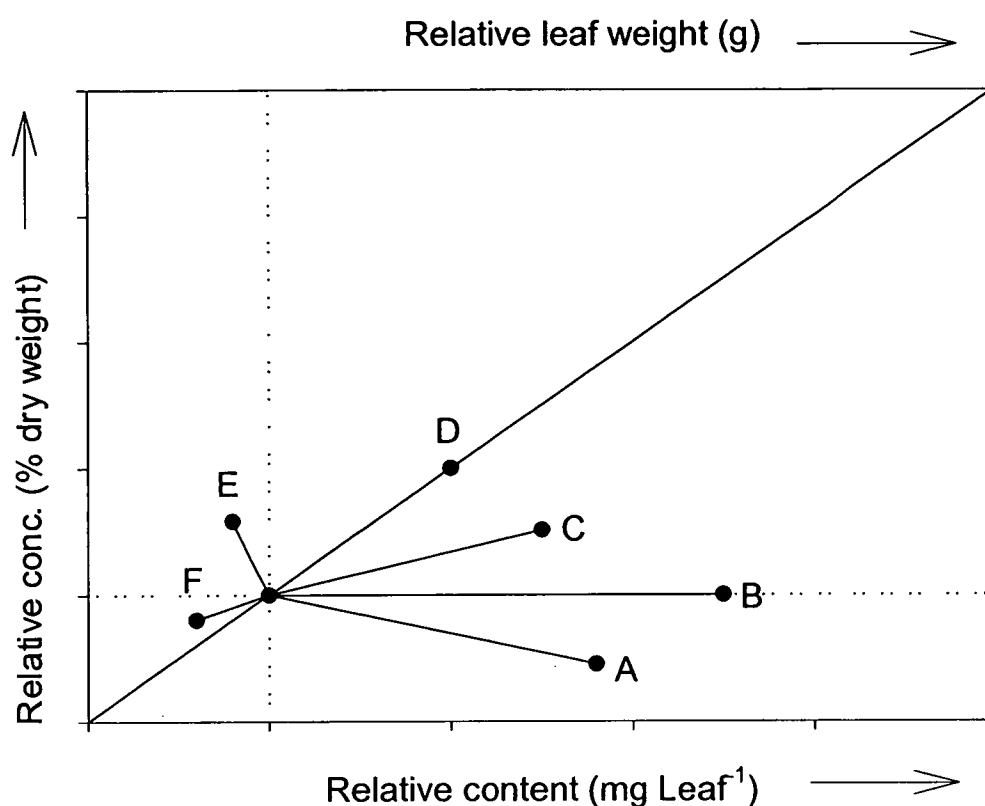
as a dilution effect whereby growth-induced increases in leaf carbohydrate reserves (increase in leaf size) increase leaf weight but not the nutrient content (Berger and Glatzel 2001). There is the potential to interpret reduced concentrations as indicators of deficiency when in fact foliar levels may be sufficient. Thus the use of critical nutrient concentrations and foliar analysis in eucalypt species has been limited beyond about two years of age (Dell *et al.* 1995).

Nutrient concentrations in foliage of young eucalypts (less than two years old) can be sensitive to changes in site fertility (Judd *et al.* 1996a) and can increase with increasing rates of nitrogen fertilisation (Schönau 1981). However, environmental factors can affect the relationship between growth and nutrient concentration, thereby making interpretation difficult (Bates 1971). Concentrations can vary seasonally, with leaf age, development and position within the crown (Lamb 1976, Bell and Ward 1984, Leuning *et al.* 1991). There is also a general decline in concentration to stable levels in older stands (Attiwill 1980, Cromer and Williams 1982, Bennett *et al.* 1997). In addition, competition-induced changes in growth can also complicate the interpretation of a given nutrient concentration.

Other methods of interpreting foliar analyses have been based on simple nutrient ratios (Cromer *et al.* 1981, Judd *et al.* 1996a) or techniques such as DRIS (Diagnosis and Recommendation Integration System) (Beaufils 1973, Sumner 1977). However, these techniques require extensive data sets and an underlying understanding of nutrient relationships, their interactions and the physiological bases behind them (Dell *et al.* 1995). Vector analysis is another approach (Weetman and Algar 1974, Weetman 1989, Haase and Rose 1995, Imo and Timmer 1999), which accounts for

changes in leaf nutrient concentration, content and leaf mass, thereby linking nutrient status and plant growth responses (Haase and Rose 1995). By combining relative changes in nutrient content, concentration and biomass, eg. leaf mass, into single vectors, the method improves the power of nutritional diagnosis based only on concentrations or nutrient ratios (Timmer and Armstrong 1987, Haase and Rose 1995). Changes in vectors with different treatments in relation to a reference treatment, eg. an N_{Zero} control, can be interpreted in terms of concentration, content and leaf size simultaneously and independently of predetermined critical levels or ratios (Figure 8.1). Vector analysis also allows for the detection of dilution effects, nutrient imbalances and interactions between elements (Timmer 1991). The use of relative changes also allows comparisons across sites (Haase and Rose 1995, Bennett *et al.* 1997).

Vector analysis has been used to study various species under nursery conditions and in the field to evaluate fertiliser response in conifers (Timmer and Armstrong 1987, Mead and Mansur 1993, Haase and Rose 1995, Imo and Timmer 1997, Keifer and Fenn 1997, Labrecque *et al.* 1998). Use of vector analysis has often been restricted to tree species with pre-formed shoots, dormant buds and determinant growth (Braekke 1996) and there has been little use in eucalypt studies (Bennett *et al.* 1997).



Types of shift	Response in			Growth	Nutrient interpretation	Nutrient diagnosis	Moisture diagnosis
	Leaf mass	Conc.	Cont.				
A	+	-	+	Increased	Dilution	Non limiting	Non limiting
B	+	0	+	Increased	Sufficiency	Non-limiting	Non limiting
C	+	+	+	Increased	Deficiency	Limiting	Possibly Limiting
D	0	+	+	No change	Luxury consumption	Non-toxic	Non limiting
E	-	++	+/-	Reduced	Excess	Toxic	Possibly limiting
F	-	-	-	Reduced	Excess	Antagonistic	Limiting

Figure 8.1 Interpretation of directional relationships between nutrient concentration (conc.), nutrient content per leaf (cont.) and leaf mass (Mead and Mansur 1993, Haase and Rose 1995, Imo and Timmer 2000)

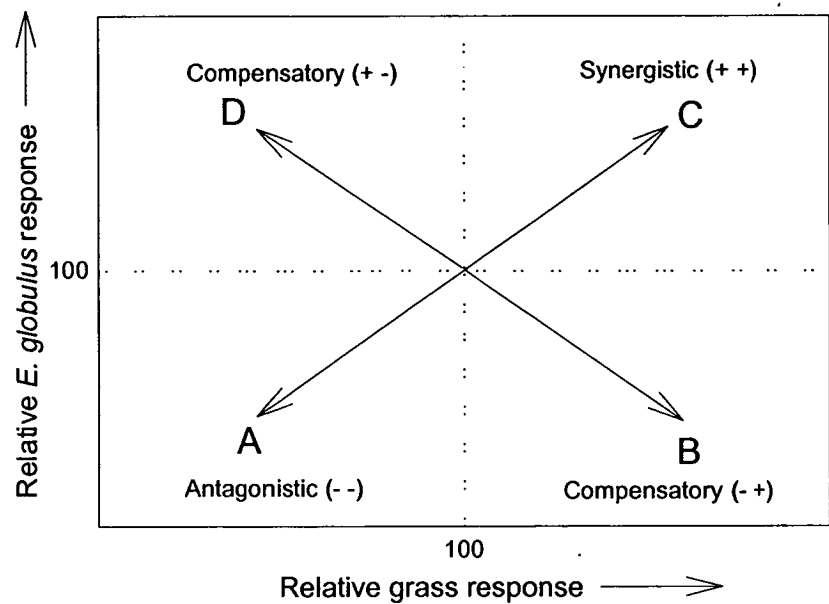
Other applications of vector analysis include non-nutrient treatment effects such as vegetation control (Mead and Mansur 1993, Imo and Timmer 1998, Imo and Timmer 1999) and soil moisture (Mead and Mansur 1993). Imo and Timmer (1998) modified the method of vector analysis, to examine weed-tree interactions directly (Vector Competition Analysis) by plotting vectors of changing biomass and nutrient uptake relative to weed-free status (Figure 8.2). The vectors show the magnitude and orientation of the biomass (B) or nutrient content (NC) response to competition type (antagonistic, synergistic and compensatory competition; Figure 8.2 Box I). Box II identifies growth and nutritional interactions for each species based on their vector ratio (Imo and Timmer 1999).

The objectives of this chapter are to determine, in a young *E. globulus* plantation (a) the effect of contrasting weed, irrigation and fertiliser treatments on foliar nutrient status, (b) the effectiveness of fertiliser application in alleviating nutrient deficiencies in weed treatments, (c) the relationship between foliar nutrient concentrations and growth in contrasting weed and irrigation treatments, and (d) evaluate vector analysis for examining the effect of grass competition on tree nutrient status.

8.2 Methods and materials

8.2.1 Weed nutrients

Samples from weed biomass harvests from experiment 1 were obtained for each plot at 10, 15 and 19 months after sowing (Chapter 3 Weed growth). Each was ground (2 mm sieve) and then digested in a mixture of sulphuric acid and hydrogen peroxide (Lowther 1980). Total nitrogen and total phosphorus concentrations (%) were



Box I: Competition responses

Vector shift	Relative response		Interaction type
	Tree	Weed	
A	-	-	Antagonism
B	-	+	Compensatory
C	+	+	Synergistic
D	-	-	Compensatory

Box II: Growth and nutritional interactions

Vector ratio (NC / B)	Relative changes in		Diagnosis
	Biomass (B)	Nutrient content (NC)	
<1	-	-	Antagonistic dilution
<1	+	+	Growth dilution
=1	+	+	Sufficiency
>1	-	+ -	Excess uptake
>1	+	+	Deficiency

Figure 8.2 Vector competition analysis, depicting relationships between tree and weed responses (from Imo and Timmer 1999). Competition – free trees and weeds are normalised to 100% and are compared with interacting plants. The vectors show the magnitude and orientation of the biomass (B) or nutrient content (NC) response to competition type (shown in Box I). Box II identifies growth and nutritional interactions for each species based on their vector ratio (Imo and Timmer 1999).

determined by Flow Injection Analysis (Lachat Instruments QuikChem 8000). Total N and P (kg ha^{-1}) in the above-ground weed biomass was calculated using equation 8.1 for N or P.

$$\text{Above-ground N or P content (kg ha}^{-1}\text{)} = \text{concentration (\%)} \times \text{biomass (kg ha}^{-1}\text{)} \quad (8.1)$$

Due to the dominance of *H. lanatus* in the weed population, only the nutrient status of grass is reported here.

8.2.3 *E. globulus* nutrients

Two leaves were collected from six trees per plot in the eight main treatments of experiment 1 at ages 5, 7, 10, 13, 15, 17, 20 and 24 months after planting. The youngest fully-expanded leaves from the upper one-third of the canopy were removed from each tree (Dell *et al.* 1995), and bulked within each plot. These were dried at 65°C for 48 h, weighed, ground (2 mm sieve) and then sub-sampled for nutrient analysis. Total N and P concentration (%) was determined by Flow Injection Analysis (Lachat Instruments QuikChem 8000) as for weeds above. Corresponding samples were taken at similar times in Experiment 2 as 1 but commenced at age 10 months and finished at age 24 months. Potassium and sodium were analysed by flame emission (Varian Spectra AA) for samples at ages 5, 7 and 10 months for Experiment 1 only.

The dry mass of leaves collected for nutrient analyses was measured to calculate leaf nutrient content using equation 8.2. Leaf mass was not available for age 10 months in experiment 2.

$$\text{Nutrient content (mg leaf}^{-1}\text{)} = \text{concentration (mg g}^{-1}\text{)} \times \text{leaf mass (g)} \quad (8.2)$$

The ratio of N:P concentrations in foliage was calculated using equation 8.3.

$$\text{N:P ratio} = \text{N concentration (\%)} / \text{P concentration (\%)} \quad (8.3)$$

8.3.3 Data analysis

Analysis of variance

For experiment 1, nutrient data (concentration, content and leaf mass) were analysed by ANOVA (Genstat 4) using a split-plot design. For Experiment 2, a randomised block design was used. Several plots in experiment 1 were excluded due to herbicide toxicity (plots 3, 37 and 46) and treated as “missing plots”. At each date, Least Significant Difference tests (LSD’s) were used to determine differences between treatments. No data transformations were required. In the results, unless specified, treatment interactions were not significant.

Regression analysis

The relationship between foliar levels of nutrients and diameter growth was determined by linear regression analysis. Diameter increments for a range of periods were regressed on foliar N and P concentration and content during and before these periods (Table 8.1). All treatments were analysed in experiment 1, with two blocks (replicates) at age seven months and three blocks thereafter. In experiment 2, all treatments and all blocks (two) were analysed for each period.

Table 8.1 Dates for regression analysis of diameter increment vs. foliar concentration and content (Experiment 1).

N fertiliser application	Foliar analysis date	Tree age (months)	Months post fertiliser application	Diameter increment period (tree age months)
March	May 97	7	2	7 – 11
	August 97	10	5	7 – 11
October	November 97	13	1	12 – 17
	January 98	15	3	12 – 17
	March 98	17	5	12 – 17
April	June 98	20	2	17 – 24

Vector analysis

Using vector analysis, the relative nutrient concentration, content and mass for each sampling date were calculated as a ratio of the control treatment (I_{Low} N_{Zero} Weeds) which was normalised to 100. These values were plotted and vectors from the control to these points added, to represent shifts in nutrient status and foliar mass (Haase and Rose 1995). Interpretation was made according to the vector shifts (direction and magnitude of the vectors) and the significance of changes in concentration, content and leaf mass. In this way nutrient requirements can be diagnosed and nutrient interactions identified.

Traditionally, vector analysis uses the N_{Zero} treatment and assumes moisture and other stresses are constant for the other treatments. In a study of the competitive effects of groundcover species on *P. radiata*, Mead and Mansur (1993) used the weed-free treatment as the reference. In another study investigating the effects of Mg fertiliser and grass on the growth and nutrition of *P. radiata*, Payn (1991) used the unfertilised, un-weeded treatment as reference. Both approaches were appropriate to each study. In the present study, the effect of N-fertiliser, irrigation and weed control

on the competitive interactions between *H. lanatus* and *E. globulus* was examined.

Therefore, $I_{Low} N_{Zero}$ Weeds treatment was used as the reference or control.

The standard vector diagram (Figure 8.1), has six vector shifts represented, along with interpretation used in the analysis of diagrams (Mead and Mansur 1993, Haase and Rose 1995, Imo and Timmer 1999). Each vector has been described as belonging to one of the 7 classes, A – F, with corresponding nutrient diagnosis listed below the figure. Both trends and significance of differences from the control treatment in terms of concentration and content are considered.

Vector direction A signifies decreasing concentration but increasing leaf mass and nutrient content, leading to a dilution of the nutrient concentration by the additional growth. A shift towards B indicates an increase in mass and content without increasing concentration and therefore signifies sufficiency. An outward shift towards C, denotes increases in mass, content and concentration, implying that initial concentrations were limiting (deficiency). Vector D indicates luxury uptake, ie. increasing concentration and content, without increasing leaf mass. Movement in direction E results from an increase in concentration with reduced leaf mass. This is a strong indication of toxic accumulation, unless associated with some other growth constraint. A shift towards F, the reverse of a shift to C, involves a depression of both concentration and mass, and would signify deficiency induced by treatment or real antagonism (Cain 1959). It may also indicate retranslocation of nutrients to newly developing leaves.

Mead and Mansur (1993) modified the vector analysis procedure because they considered that in competition experiments, trees grow at various levels of competition and therefore are likely to be different in both moisture and nutrient status. They changed the orientation of the vector and added two more vectors to account for changes in both nutrient and moisture status in their competition study. In the present study, this modification was not necessary as vector length, and proximity to the main axes and zones enabled appropriate interpretation. Possible diagnoses for both nutrients and plant moisture status for the basic six vectors are given in Figure 8.1.

In Experiment 1, seven vectors were associated with each of the seven treatments (excluding the reference or control, I_{Low} N_{Zero} Weeds). The significance of treatment effects on N concentration, N content and leaf mass could be determined from analysis (ANOVA) of these individual variables and these then used to interpret the associated vectors within the diagrams. These data are not presented in the results but rather, a simplification of the vector diagrams was carried out whereby only those treatments that were significantly different from the reference were plotted on each diagram. Where there was a significant third order interaction (eg. $I \times N \times W$), all treatment points were plotted on the diagram. To determine which vectors were significant in terms of direction and magnitude, an analysis of variance (ANOVA) of the relative foliar concentration, content and leaf mass was carried out for each sampling date (age 7, 10, 13, 15, 17 and 20 months). A large arrow (or arrows) was added to each diagram to highlight the main direction and magnitude of the significant vectors. LSD's were also calculated for relative N concentration and relative N content (for each sample date) and used to construct bi-directional error

bars that were added to vector diagrams. The same procedure was carried out for experiment 2, where there were four N-fertiliser rates other than the control (N_{Zero} W). In this case all treatment points were presented on each vector diagram and a large arrow added to indicate the trends where there were significant differences.

Vector analysis in Experiment 1, used foliar analysis data from age 5 – 20 months, and for experiment 2, data from age 13 – 24 months (Table 8.2). The table also shows three dates of N application, the foliar sampling dates, tree age and months since last nitrogen application. Analysis was carried out for nitrogen and phosphorus. The foliar nutrient levels of weeds was also analysed for each biomass harvest date.

Vector competition analysis

Combined analyses for *H. lanatus* and *E. globulus* using vector competition analysis (Imo and Timmer 1998) examined the weed - tree interaction more closely. This method evaluates weed and tree interactions in a bivariate model depicting vectors of changing biomass and nutrient uptake relative to competition-free status (Imo and Timmer 1999). Figure 8.2 shows the model with vectors of changing biomass and nutrient uptake relative to weed-free status. The vectors show the magnitude and orientation of the biomass (B) or nutrient content (NC) response to competition type (antagonistic, synergistic and compensatory competition) as shown in Figure 8.2 Box I. Grass above-ground biomass was expressed as a percentage of the control treatment (I_{Low} N_{Zero} Weeds), while *E. globulus* leaf mass (a surrogate for biomass) was expressed as a percentage of I_{Low} N_{Zero} WF treatments. This was also done for nutrient content (N, P). These data were then plotted on a bivariate graph with relative tree response on the Y-axis and relative grass response on the X-axis. Figure

8.2, Box II identifies growth and nutritional interactions for each species based on their vector ratio (nutrient content / biomass) (Imo and Timmer 1999). Biomass, N and P content were sampled for both *H. lanatus* and *E. globulus* at tree age 10, 13 and 17 months.

Table 8.2 Vector analysis dates (time of nitrogen application and foliar sampling)

N fertiliser Application	Foliar sampling date	Tree age (months)	Months post fertiliser application
	March 97	5	-1
March 97	May 97	7	2
	August 97	10	5
October 97	November 97	13	1
	January 98	15	3
	March 98	17	5
April 98	June 98	20	2
	October 98	24	6

8.3 Results

8.3.1 N and P status of *E. globulus*

Foliar N concentration

Without fertiliser (N_{Zero}) *E. globulus* foliar N concentrations were significantly lower in W compared to WF treatments during the first 12 – 18 months of growth (Figure 8.3a; Table 8.3). A significant, second order nitrogen x weed interaction occurred at ages 10 and 13 months. N-fertilisation increased foliar N concentrations in the absence of weed control, but it had no effect in the weed-free treatment. N_{High} W had the highest concentrations at 10 months, while N_{Zero} WF treatments had the highest concentration at 13 months. N_{Zero} W treatments had the lowest concentrations at both ages. On other dates of sampling, weeds and nitrogen were the significant effects.

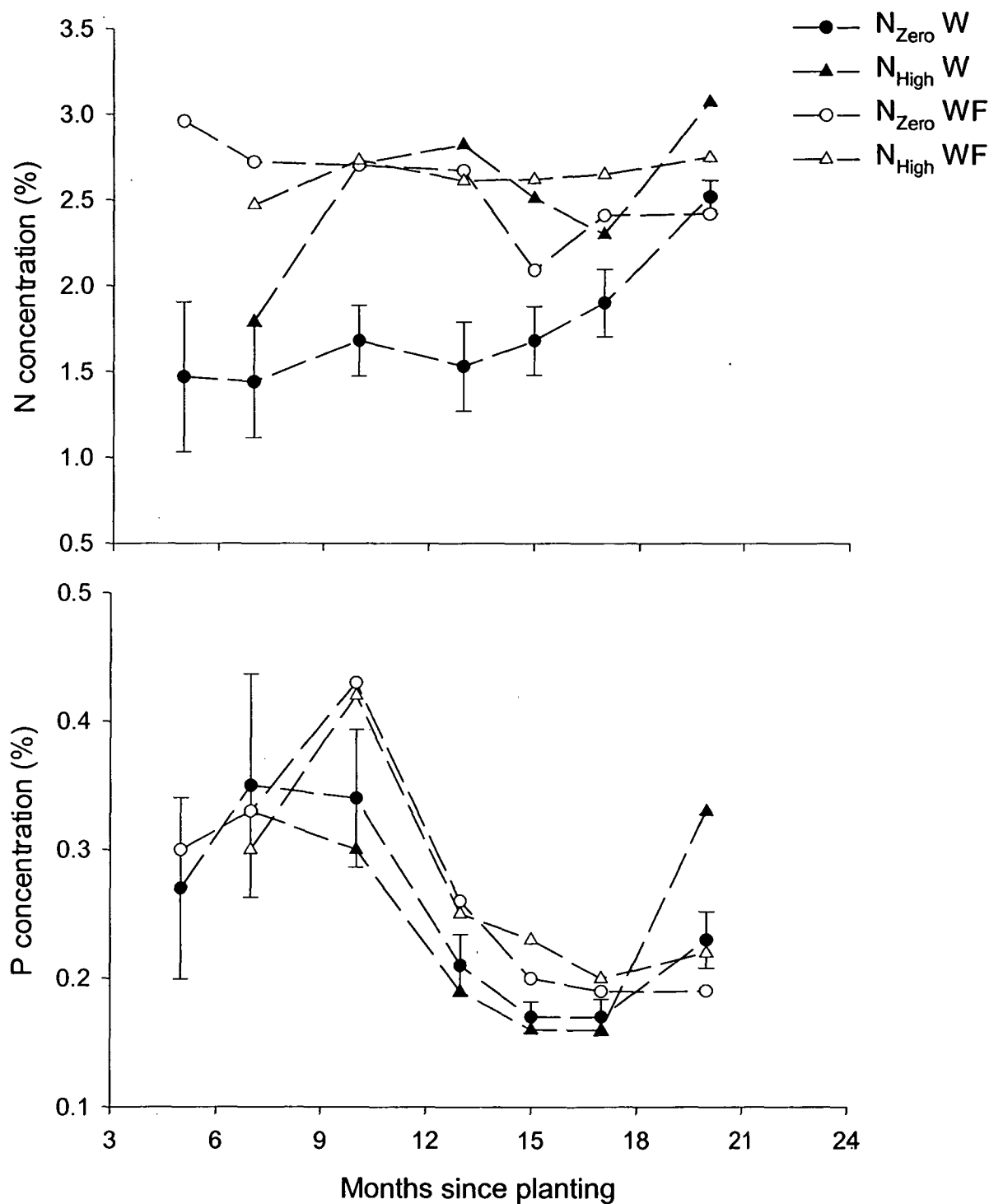


Figure 8.3 The effect of nitrogen application and weeds on *E. globulus* foliar nutrient concentrations (%) in experiment 1. (a) N and (b) P. Error bars are LSD ($p=0.05$)

Table 8.3 Experiment 1. Effect of irrigation, N fertiliser and weeds on *E. globulus* Leaf N concentration (%)

Treatment	Date and months since planting						
	Mar-97 5	May-97 7	Aug-97 10	Nov-97 13	Jan-98 15	Mar-98 17	Jun-98 20
I _{Low} N _{Zero} W	1.72	1.38	1.77	1.69	1.82	1.86	2.52
I _{Low} N _{High} W		1.68	3.02	2.67	2.51	2.32	3.07
I _{High} N _{Zero} W	1.23	1.49	1.60	1.36	1.55	1.95	2.52
I _{High} N _{High} W		1.90	2.40	2.96	2.51	2.27	2.85
I _{Low} N _{Zero} WF	3.16	2.75	2.86	2.30	2.08	2.61	2.47
I _{Low} N _{High} WF		2.64	2.89	2.55	2.66	2.73	2.91
I _{High} N _{Zero} WF	2.77	2.68	2.55	3.03	2.11	2.22	2.36
I _{High} N _{High} WF		2.29	2.57	2.68	2.57	2.56	2.68
Source of variation	Probability > F						
Water	0.051	0.567	0.154	0.416	0.138	0.203	0.034
Nitrogen		0.784	0.002	0.003	<0.001	0.062	<0.001
Weeds	0.009	0.002	0.002	0.017	0.091	0.003	0.044
Water x N		0.829	0.409	0.990	0.975	0.900	0.131
Water x weeds	0.879	0.361	0.781	0.205	0.494	0.265	0.686
N x weeds		0.160	0.003	0.002	0.197	0.826	0.568
Water x N x weeds		0.627	0.427	0.094	0.626	0.480	0.638
Std Error	0.331	0.326	0.279	0.354	0.220	0.223	0.092

At age five months, concentrations were 1.47 % and 2.96 % for weedy (W) and weed-free (WF) treatments, respectively. At this time trees receiving I_{Low} had 22 % higher N concentrations than I_{High} treatments, but the interaction between weeds and irrigation was not significant. Foliar N concentrations rapidly increased in N_{High} treatments between age 7 and 10 months in response to N-fertiliser application at age six months (Figure 8.3a). Following this period, *E. globulus* foliar N concentration was 2 – 2.8%, for all treatments except N_{Zero} W which steadily increased from < 2%. By age 20 months, all treatments were within the range 2.4 – 3.1 %.

Foliar P concentration

Foliar P concentrations declined during the second year of growth, with W treatments being significantly lower than WF treatments from age 10 – 17 months (Figure 8.3b; Table 8.4). There was a significant second order nitrogen x weed interaction at age 15 months with higher P concentrations in the N_{Zero} W than N_{High} W treatments, contrasting with no effect in the WF treatments. At 20 months W treatments tended to increase, especially N_{High} W, following a similar trend to foliar N concentrations. A seasonal trend was apparent with higher concentrations up to age 10 months (0.28 to 0.50%) then a decrease over the summer / autumn (0.15 to 0.20 %), before rising again in late winter (age 20 months).

Table 8.4 Experiment 1. Effect of irrigation, N fertiliser and weeds on *E. globulus* Leaf P concentration (%).

Treatment	Date and months since planting						
	Mar-97 5	May-97 7	Aug-97 10	Nov-97 13	Jan-98 15	Mar-98 17	Jun-98 20
I _{Low} N _{Zero} W	0.24	0.36	0.33	0.23	0.16	0.16	0.23
I _{Low} N _{High} W		0.36	0.31	0.17	0.16	0.15	0.35
I _{High} N _{Zero} W	0.30	0.34	0.35	0.20	0.18	0.18	0.23
I _{High} N _{High} W		0.30	0.28	0.21	0.17	0.17	0.24
I _{Low} N _{Zero} WF	0.33	0.33	0.49	0.26	0.19	0.20	0.19
I _{Low} N _{High} WF		0.30	0.50	0.25	0.23	0.20	0.22
I _{High} N _{Zero} WF	0.28	0.32	0.38	0.27	0.20	0.19	0.19
I _{High} N _{High} WF		0.29	0.33	0.25	0.23	0.20	0.21
Source of variation	Probability > F						
Water	0.859	0.029	0.327	0.676	0.316	0.874	0.278
Nitrogen		0.658	0.476	0.276	0.173	0.998	0.058
Weeds	0.562	0.636	0.015	0.006	<0.001	0.010	0.023
Water x N		0.856	0.462	0.423	0.816	0.770	0.204
Water x weeds	0.333	0.766	0.101	0.986	0.742	0.243	0.417
N x weeds		0.888	0.750	0.679	0.034	0.479	0.348
Water x N x weeds		0.827	0.960	0.323	0.901	0.825	0.315
Std Error	0.064	0.087	0.085	0.032	0.015	0.021	0.298

Foliar N:P ratio

A significant second order nitrogen x weeds interaction occurred from 10 – 17 months after planting where N-fertiliser increased N:P ratios in the presence but not absence of weeds (Figure 8.4; Table 8.5). Seasonal trends were apparent with a winter low and summer high. At age seven months N:P was low (5.7) in N_{Zero} W treatments but then increased to a maximum of 11.2 at age 17 months. In N_{High} W treatments N:P started at 5.4 but following the second N-fertiliser application, peaked at 15 – 16 by age 13 – 15 months. By age 20 months this had declined to 9.6. In WF treatments, N:P initially declined from 9.8 to 6.7 at age 10 months, before stabilising at 12 – 13 by age 17 months.

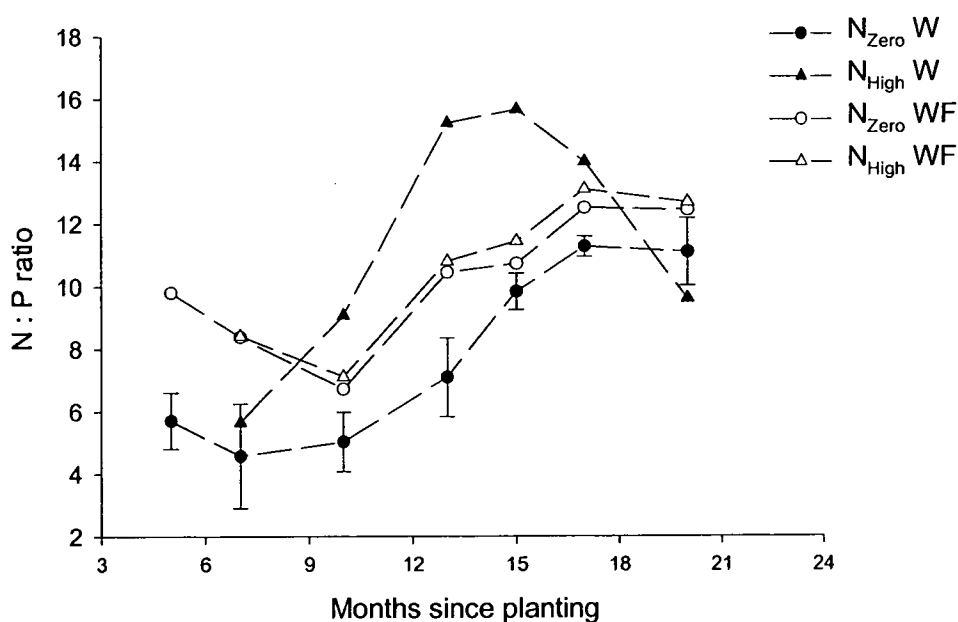


Figure 8.4 The effect of nitrogen application and weeds on *E. globulus* foliar N:P ratio (experiment 1). Error bars are LSD ($p=0.05$)

Table 8.5 Experiment 1. Effect of irrigation, N fertiliser and weeds on *E. globulus*
Foliar N:P ratio

Treatment	Date and months since planting						
	Mar-97	May-97	Aug-97	Nov-97	Jan-98	Mar-98	Jun-98
	5	7	10	13	15	17	20
I _{Low} N _{Zero} W	7.0	4.2	5.5	7.6	11.0	11.6	11.0
I _{Low} N _{High} W		4.5	9.7	16.0	16.0	14.6	9.0
I _{High} N _{Zero} W	4.4	4.5	4.6	6.6	8.6	10.9	11.1
I _{High} N _{High} W		6.3	8.5	14.5	15.2	13.4	10.1
I _{Low} N _{Zero} WF	9.7	8.4	6.6	9.5	10.8	13.0	12.4
I _{Low} N _{High} WF		8.9	6.2	10.6	11.7	13.3	12.9
I _{High} N _{Zero} WF	9.9	8.3	6.8	11.4	10.6	12.0	12.5
I _{High} N _{High} WF		7.9	8.0	11.0	11.1	12.8	13.0
Source of variation	Probability > F						
Water	0.169	0.314	0.981	0.878	0.058	0.246	0.546
Nitrogen		0.586	0.004	<0.001	<0.001	<0.001	0.689
Weeds	0.003	0.015	0.834	0.525	<0.001	0.421	0.015
Water x N		0.944	0.584	0.573	0.429	0.955	0.853
Water x weeds	0.086	0.448	0.117	0.158	0.124	0.618	0.880
N x weeds		0.611	0.012	<0.001	<0.001	<0.001	0.266
Water x N x weeds		0.739	0.453	0.766	0.202	0.266	0.866
Std Error	0.912	1.933	1.231	1.636	0.760	0.422	1.248

K and Na concentration (%)

There was no significant difference between treatments for foliar K concentration at ages five and seven months though there was a trend for higher concentrations in weed-free treatments (0.62 to 0.65% and 0.74 to 0.8% for weedy and weed-free treatments, respectively). At age 10 months, I_{Low} treatments had higher K concentrations than I_{High} treatments (0.69% and 0.65%, respectively) (data not shown). These concentrations for all treatments are within or slightly above the deficiency range (0.4% – 0.7%; Dell *et al.* 1995).

Foliage Na concentrations were significantly lower ($p=0.005$) in weed-free treatments receiving I_{Low} at age seven months (0.54%) than in other treatments. At

age 10 months, Na was significantly higher ($p=0.003$) in unfertilised compared to fertilised treatments (0.62% and 0.55%, respectively). These concentrations are well below toxicity levels for foliage (1.0%; Lambert and Turner 2000).

8.3.2 Leaf mass and nutrient content of *E. globulus*

Leaf mass

Weeds, nitrogen fertiliser and irrigation had a strong influence on mean leaf mass (Figure 8.5a; Table 8.6). A significant third order water x nitrogen x weeds interaction ($p=0.044$) occurred at age 17 months, which showed that N-fertiliser increased leaf mass for most treatments combinations of I and W, but it was related to decreased leaf mass in $I_{Low} N_{Zero}$ WF treatments. At age 15 months a significant second order nitrogen x weed interaction occurred ($p=0.007$) with leaf mass decreased in WF treatments but increased in W treatments in response to N_{High} and I_{High} . The leaf mass was consistent with tree growth in relation to weed, irrigation and fertiliser treatments (Chapter 4). In unfertilised W treatments, leaf mass ($g\ leaf^{-1}$) remained steady over time and was generally below $I_{High} N_{High}$ W treatments to age 20 months. In WF treatments, leaf mass was generally twice the mass of W treatments during the first year of growth. A seasonal effect was observed at age 12 months in the second spring; leaf mass increased and this was associated with increased growth. N_{High} WF trees tended to have lower leaf mass than N_{Zero} WF trees. (Figures 8.6 and 8.7).

N content

Changes in N content reflected changes in leaf mass (Figure 8.5 b, Table 8.7). A significant third order water x nitrogen x weeds interaction ($p=0.018$) occurred at age

20 months. This highlighted an increasing N content in N-fertilised treatments except under I_{High} W treatments where the N_{High} had decreased relative to N_{Zero} treatments. At 15 months a significant second order nitrogen x weeds interaction ($p=0.015$) was present. N content significantly increased due to N-fertiliser in weedy treatments but not in weed-free treatments. Leaf nitrogen content in N_{Zero} W treatments was 3 mg N leaf⁻¹ at age five months and had increased to 8 mg leaf⁻¹ at age 20 months (Figure 8.5b; Table 8.7). In N_{High} W treatments, N content was 9 -12 mg leaf⁻¹ from age 10

Table 8.6 Experiment 1. Effect of irrigation, N fertiliser and weeds on *E. globulus*
Leaf mass (g)

Treatment	Date and months since planting						
	Mar-97	May-97	Aug-97	Nov-97	Jan-98	Mar-98	Jun-98
	5	7	10	13	15	17	20
$I_{\text{Low}} N_{\text{Zero}} W$	0.19	0.34	0.34	0.30	0.29	0.37	0.29
$I_{\text{Low}} N_{\text{High}} W$		0.29	0.31	0.26	0.44	0.42	0.49
$I_{\text{High}} N_{\text{Zero}} W$	0.24	0.27	0.31	0.29	0.31	0.40	0.39
$I_{\text{High}} N_{\text{High}} W$		0.39	0.42	0.32	0.45	0.56	0.42
$I_{\text{Low}} N_{\text{Zero}} WF$	0.44	0.61	0.52	0.63	1.05	0.79	1.10
$I_{\text{Low}} N_{\text{High}} WF$		0.48	0.60	0.56	0.83	1.04	0.89
$I_{\text{High}} N_{\text{Zero}} WF$	0.54	0.56	0.48	0.66	1.09	0.99	0.84
$I_{\text{High}} N_{\text{High}} WF$		0.28	0.57	0.62	0.93	0.88	0.96
Source of variation	Probability > F						
Water	0.352	0.643	0.972	0.689	0.576	0.662	0.186
Nitrogen		0.300	0.049	0.373	0.656	0.105	0.766
Weeds	0.004	0.079	<0.001	<0.001	<0.001	<0.001	<0.001
Water x N		0.949	0.239	0.542	0.755	0.234	0.655
Water x weeds	0.662	0.352	0.179	0.794	0.629	0.543	0.517
N x weeds		0.158	0.520	0.523	0.007	0.769	0.232
Water x N x weeds		0.337	0.289	0.771	0.771	0.044	0.176
Std Error	0.076	0.156	0.056	0.093	0.100	0.100	0.132

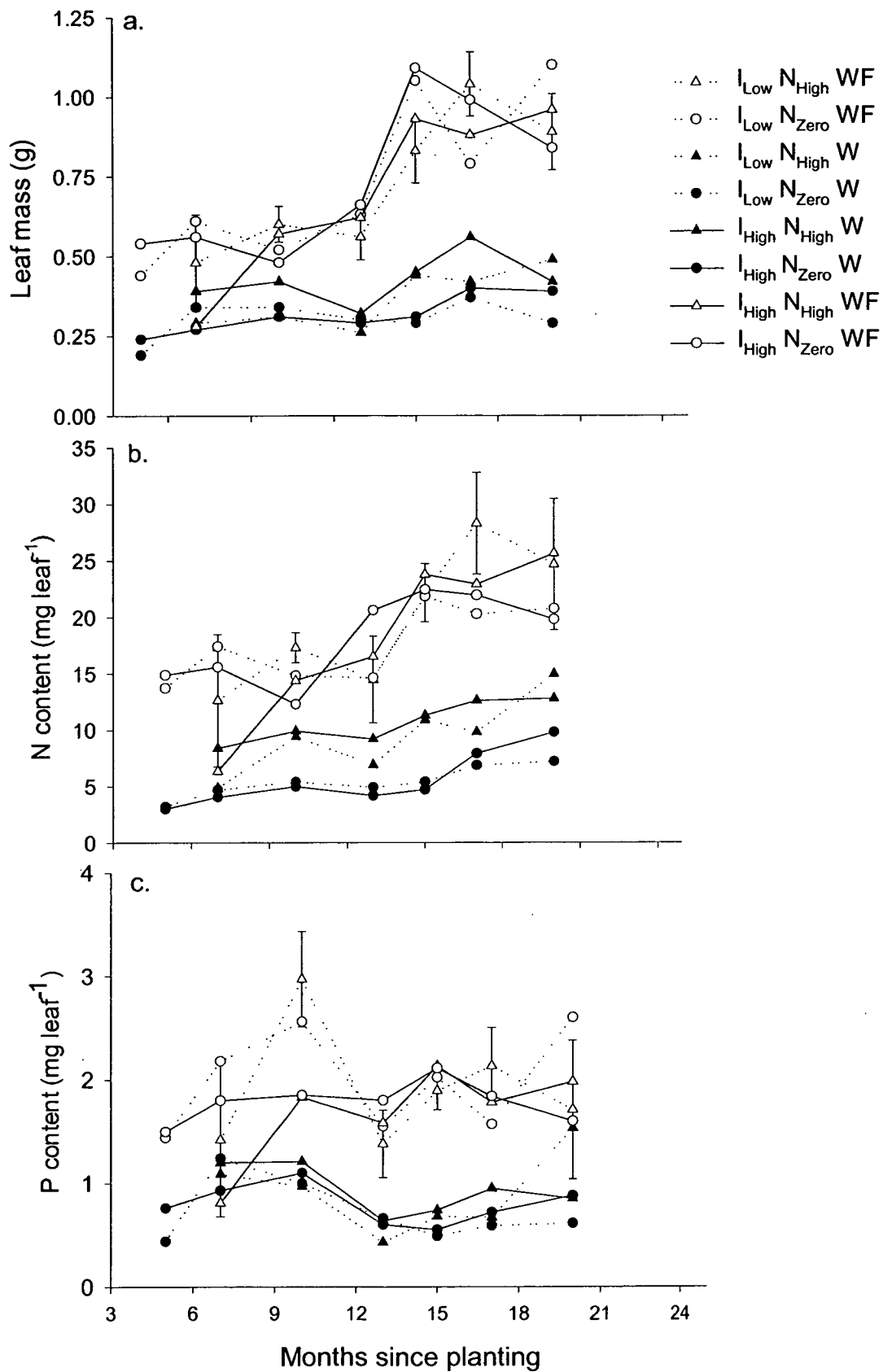


Figure 8.5 *E. globulus* (a) leaf mass (b) N content (c) P content in experiment 1. Error bars are LSD (p=0.05)

months and ran parallel to the N_{Zero} treatments to age 20 months. Within W treatments, N content increased sooner under I_{High} than I_{Low} , suggesting a role of water in the uptake of soil nitrogen. In WF treatments at age five months N content was 260 % higher than in W treatments, and significant differences remained between W and WF treatments throughout the study.

Table 8.7 Experiment 1. Effect of irrigation, N fertiliser and weeds on *E. globulus*
Leaf N content (mg leaf⁻¹)

Treatment	Date and months since planting						
	Mar-97 5	May-97 7	Aug-97 10	Nov-97 13	Jan-98 15	Mar-98 17	Jun-98 20
$I_{Low} N_{Zero} W$	3.20	4.69	5.38	4.90	5.38	6.85	6.70
$I_{Low} N_{High} W$		4.86	9.40	6.89	10.85	9.81	14.96
$I_{High} N_{Zero} W$	3.00	4.06	4.96	4.16	4.69	7.91	9.80
$I_{High} N_{High} W$		8.39	9.91	9.19	11.29	12.60	10.00
$I_{Low} N_{Zero} WF$	13.73	17.41	14.81	14.61	21.85	20.28	20.75
$I_{Low} N_{High} WF$		12.62	17.31	14.46	22.15	28.28	24.68
$I_{High} N_{Zero} WF$	14.89	15.60	12.28	20.62	22.44	21.93	19.80
$I_{High} N_{High} WF$		6.34	14.37	16.50	23.77	22.92	25.65
Source of variation	Probability > F						
Water		0.598	0.068	0.402	0.330	0.933	0.608
Nitrogen		0.405	<0.001	0.622	0.005	0.028	0.257
Weeds		0.031	<0.001	<0.001	<0.001	<0.001	<0.001
Water x N		0.977	0.847	0.868	0.304	0.358	0.664
Water x weeds		0.343	0.060	0.254	0.899	0.356	0.388
N x weeds		0.133	0.126	0.060	0.014	0.925	0.065
Water x N x weeds		0.450	0.621	0.221	0.528	0.279	0.018
Std Error	1.66	4.95	1.21	3.27	2.33	3.86	3.92

P content

Leaf P content (mg leaf⁻¹) was up to 170% higher in WF treatments than in W treatments (Figure 8.5c; Table 8.8). A significant third order water x nitrogen x weed interaction ($p=0.033$) occurred at age 20 months where the leaf P content of $I_{Low} N_{High} W$ treatments increased greater than other W treatments. At age 15 months and

10 months there were significant nitrogen x weed and water x weed interactions respectively. At 15 months the lowest P contents occurred in N_{Zero} W treatments while at age 10 months, I_{High} increased P content in W but not WF treatments.

K and Na content (mg leaf⁻¹)

K content (mg leaf⁻¹) was significantly higher in weed-free treatments than weedy treatments at age five and 10 months ($p=0.004$; 4.18 and 1.38 mg leaf⁻¹ and $p<0.001$; 3.65 and 2.30 mg leaf⁻¹, respectively). No significant differences occurred at age seven months due to smaller leaf sizes in fertilised weed-free plots receiving high irrigation (data not shown). Na content (mg leaf⁻¹) was significantly lower in weedy treatments than weed-free treatments at five and 10 months ($p=0.010$; 4.25 and 1.5 mg leaf⁻¹ and $p=0.043$; 3.1 and 2.1 mg leaf⁻¹, respectively) but not at seven months.



Figure 8.6 *E. globulus* (age six months) growing in weedy plot (height 0.4m)



Figure 8.7 *E. globulus* (age six months) growing in weed-free plot (height 0.7 m)

Table 8.8 Experiment 1. Effect of irrigation, N fertiliser and weeds on *E. globulus* Leaf P content (mg leaf⁻¹)

Treatment	Date and months since planting						
	Mar-97	May-97	Aug-97	Nov-97	Jan-98	Mar-98	Jun-98
	5	7	10	13	15	17	20
I _{Low} N _{Zero} W	0.44	1.24	1.00	0.66	0.49	0.59	0.61
I _{Low} N _{High} W		1.09	0.97	0.43	0.72	0.75	1.54
I _{High} N _{Zero} W	0.76	0.93	1.10	0.60	0.55	0.72	0.88
I _{High} N _{High} W		1.20	1.21	0.64	1.03	0.95	0.86
I _{Low} N _{Zero} WF	1.44	2.18	2.56	1.55	2.02	1.57	2.6
I _{Low} N _{High} WF		1.42	2.97	1.38	1.89	2.13	1.71
I _{High} N _{Zero} WF	1.50	1.80	1.85	1.80	2.11	1.84	1.59
I _{High} N _{High} WF		0.81	1.83	1.58	2.13	1.78	1.98
Source of variation	Probability > F						
Water	0.571	0.319	0.142	0.524	0.139	0.785	0.298
Nitrogen		0.286	0.610	0.210	0.112	0.128	0.629
Weeds	<0.001	0.254	<0.001	<0.001	<0.001	<0.001	0.003
Water x N		0.894	0.747	0.650	0.286	0.376	0.676
Water x weeds	0.109	0.589	0.035	0.504	0.905	0.447	0.690
N x weeds		0.225	0.744	0.661	0.043	0.910	0.121
Water x N x weeds		0.654	0.553	0.478	0.781	0.225	0.033
Std Error	0.285	0.692	0.428	0.224	0.167	0.319	0.374

8.3.3 Foliar nutrients as affected by N-fertiliser rate

Foliar levels of nutrients in *E. globulus* in experiment 2 were similar to experiment 1. Seasonal variation was apparent and concentrations generally increased with rates of N application (Figure 8.8a; Table 8.9). After starting at 1.62 % (± 0.34) across treatments at age 10 months, there was a strong linear response to rate of N-fertiliser application at age 13 and 14 months ($p<0.001$; $r^2=0.94$ and $r^2=0.88$ respectively) (Figure 8.9). The highest concentrations (2.6 % and 2.2 %) at these times corresponded with the highest N application rate (N_{1200} ; first application @ 600 kg N ha^{-1}). Responses became non-linear after this time (quadratic curves fitted), peaking at the N_{400} rate (first application @ 200 kg N ha^{-1}) at age 15 and 17 months ($p=0.003$ and $r^2=0.75$; $p=0.120$ and $r^2=0.30$ respectively). These responses held, following the second N- fertiliser application at age 20 months ($p=0.011$ and $r^2=0.64$), however by age 24 months there was no clear relationship between N rate and foliar N concentration and the mean N concentration was 2.15 % (± 0.17).

Table 8.9 Experiment 2. Effect of irrigation, N fertiliser and weeds on *E. globulus*
Leaf N concentration (%)

Treatment	Date and months since planting						
	Aug-97	Nov-97	Dec-97	Jan-98	Mar-98	Jun-98	Oct-98
	10	13	14	15	17	20	24
N _{Zero}	1.71	1.21	1.11	1.08	1.82	2.15	2.12
N ₂₀₀	1.32	1.47	1.26	1.49	2.32	2.52	1.94
N ₄₀₀	1.73	1.77	1.49	2.02	2.26	2.76	2.33
N ₈₀₀	1.43	2.23	1.81	2.23	2.65	2.62	2.27
N ₁₂₀₀	1.92	2.59	2.12	2.04	2.30	2.56	2.12
Source of variation		Probability > F					
Treatment	0.491	0.001	0.012	0.031	0.134	0.070	0.289
Std Error	0.336	0.116	0.152	0.231	0.227	0.142	0.173

Table 8.10 Experiment 2. Effect of irrigation, N fertiliser and weeds on *E. globulus* Leaf P concentration (%)

Treatment	Date and months since planting						
	Aug-97	Nov-97	Dec-97	Jan-98	Mar-98	Jun-98	Oct-98
	10	13	14	15	17	20	24
N _{Zero}	0.34	0.19	0.16	0.15	0.18	0.21	0.19
N ₂₀₀	0.25	0.18	0.15	0.16	0.18	0.22	0.20
N ₄₀₀	0.37	0.18	0.17	0.19	0.18	0.22	0.23
N ₈₀₀	0.25	0.19	0.16	0.16	0.17	0.21	0.27
N ₁₂₀₀	0.23	0.21	0.17	0.14	0.16	0.17	0.26
Source of variation				Probability > F			
Treatment	0.102	0.300	0.651	0.289	0.739	0.294	0.041
Std Error	0.043	0.012	0.011	0.019	0.020	0.019	0.018

There were no significant differences between treatments in foliar P concentrations between ages 13 - 20 months (Figure 8.8b; Table 8.10). However, at age 10 months, N₀ and N₂₀₀ had the highest P concentrations, which was probably related to low weed cover in two particular plots. There was no increase in P concentration immediately after each of the two N fertiliser applications at age 12 and 18 months respectively. Across treatments, P concentration was 0.19 % (± 0.01) at age 13 months and 0.23 % (± 0.02) at age 24 months which could be regarded as adequate (0.15 – 0.38%; Dell *et al.* 1995).

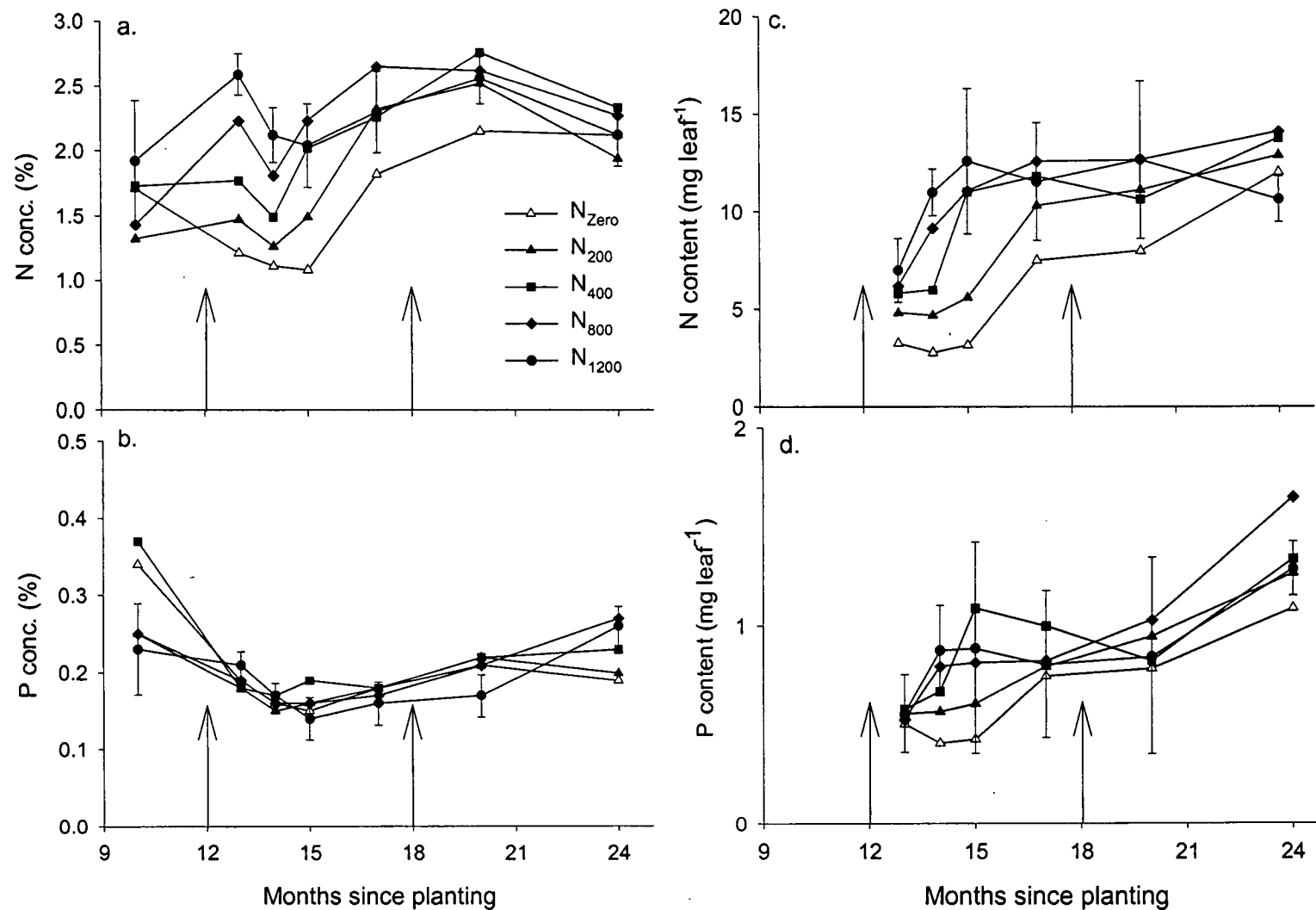


Figure 8.8 Experiment 2. *E. globulus* (a) N and (b) P concentration (c) N and (d) P content. Arrows indicate N fertiliser application at 12 and 18 months after planting. Error bars are LSD ($p=0.05$)

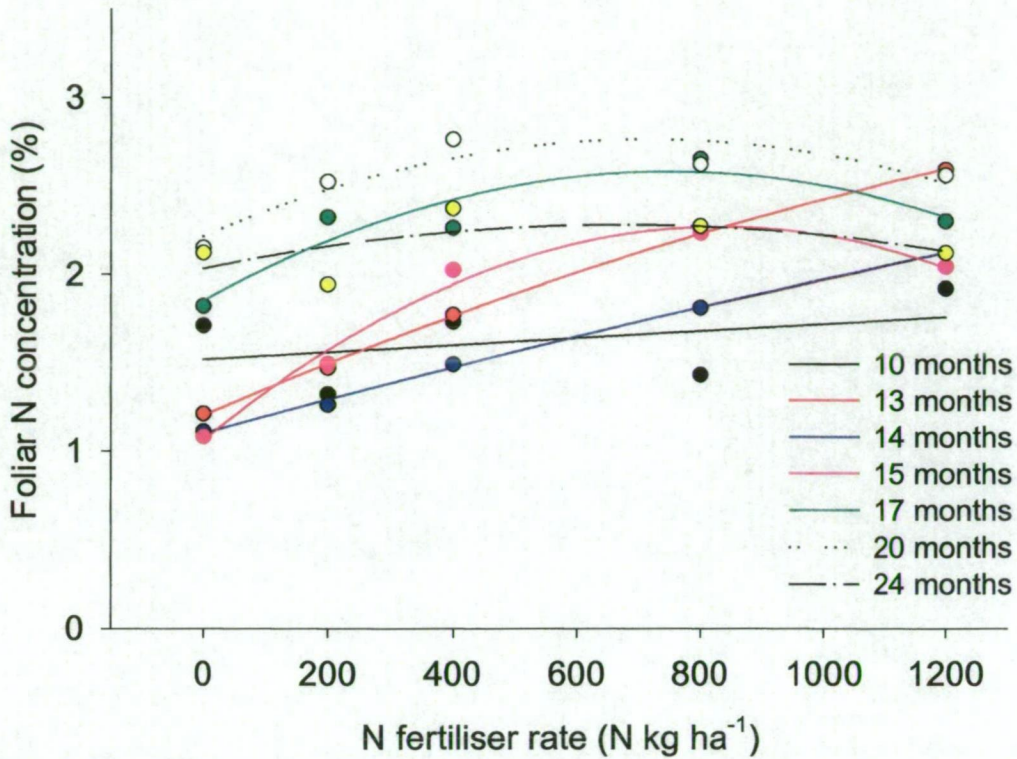


Figure 8.9 Response of *E. globulus* foliar N concentration to rate of N-fertiliser.

Leaf mass increased with increasing nitrogen rate (Table 8.11). In N_{Zero} trees, leaf mass increased steadily with time, while in N_{High} trees it increased quickly after N-fertilisation at age 12 months and then slowed. Between age 12 – 20 months there was no significant difference in leaf mass between treatments. This corresponded to rapid linear increases in N content with N-fertiliser rate at age 13 and 14 months ($p=0.019$ and $p<0.001$ respectively) (Figure 8.8c; Table 8.12 and Figure 8.9). Non-linear responses were apparent at age 15 and at 17 months. However, the curve was significant at 15 months ($p=0.39$) and non-significant at age 17 months ($p=0.139$). There was no strong relationship after this date.

Table 8.11 Experiment 2. Effect of irrigation, N fertiliser and weeds on *E. globulus*
Leaf mass (g)

Treatment	Date and months after planting					
	Nov-97 13	Dec-97 14	Jan-98 15	Mar-98 17	Jun-98 20	Oct-98 24
N _{Zero}	0.27	0.25	0.29	0.41	0.37	0.56
N ₂₀₀	0.33	0.37	0.38	0.44	0.45	0.66
N ₄₀₀	0.32	0.41	0.55	0.53	0.38	0.59
N ₈₀₀	0.28	0.51	0.50	0.49	0.49	0.62
N ₁₂₀₀	0.27	0.52	0.61	0.50	0.49	0.50
Source of variation			Probability > F			
Treatment	0.924	0.126	0.452	0.877	0.909	0.020
Std Error	0.094	0.083	0.174	0.131	0.169	0.030

Table 8.12 Experiment 2. Effect of irrigation, N fertiliser and weeds on *E. globulus*
Leaf N content (mg leaf⁻¹)

Treatment	Date and months since planting					
	Nov-97 13	Dec-97 14	Jan-98 15	Mar-98 17	Jun-98 20	Oct-98 24
N _{Zero}	3.25	2.77	3.14	7.48	7.96	11.99
N ₂₀₀	4.80	4.67	5.59	10.30	11.10	12.86
N ₄₀₀	5.81	5.97	11.00	11.79	10.62	13.74
N ₈₀₀	6.18	9.14	11.06	12.56	12.64	14.07
N ₁₂₀₀	6.98	10.97	12.56	11.52	12.63	10.62
Source of variation			Probability > F			
Treatment	0.342	0.011	0.209	0.554	0.772	0.064
Std Error	1.637	1.193	3.72	3.020	4.05	1.180

Table 8.13 Experiment 2. Effect of irrigation, N fertiliser and weeds on *E. globulus* Leaf P content (mg leaf⁻¹)

Treatment	Date and months since planting					
	Nov-97	Dec-97	Jan-98	Mar-98	Jun-98	Oct-98
	13	14	15	17	20	24
N _{Zero}	0.51	0.41	0.43	0.75	0.79	1.09
N ₂₀₀	0.56	0.57	0.61	0.80	0.95	1.27
N ₄₀₀	0.58	0.67	1.09	1.00	0.83	1.34
N ₈₀₀	0.53	0.80	0.82	0.83	1.03	1.65
N ₁₂₀₀	0.56	0.88	0.89	0.81	0.85	1.29
Source of variation			Probability > F			
Treatment	0.982	0.188	0.550	0.889	0.953	0.021
Std Error	0.143	0.162	0.385	0.266	0.358	0.098

Table 8.14 Experiment 2. Effect of irrigation, N fertiliser and weeds on *E. globulus* foliar N:P ratio

Treatment	Date and months since planting						
	Aug-97	Nov-97	Dec-97	Jan-98	Mar-98	Jun-98	Oct-98
	10	13	14	15	17	20	24
N _{Zero}	5.1	6.4	6.8	7.3	9.9	10.2	11.2
N ₂₀₀	5.3	8.3	8.3	9.1	12.7	11.7	9.9
N ₄₀₀	4.7	9.9	8.8	10.5	12.2	12.8	10.3
N ₈₀₀	5.7	11.7	11.4	13.6	15.4	12.3	8.5
N ₁₂₀₀	8.3	12.5	12.6	14.1	14.2	14.9	8.2
Source of variation		Probability > F					
Treatment	0.111	0.003	0.043	<0.001	0.057	0.026	0.257
Std Error	1.022	0.645	1.288	0.418	1.185	0.794	1.260

There were no significant differences in P content between treatments until age 24 months (Figure 8.8d; Table 8.13), though N₀ consistently had the lowest content. An increase in P content occurred after N application at age 12 months, then declined, and then a further increase was apparent at age 20 months. There was a significantly higher P content in N₈₀₀ than other treatments by age 24 months ($p=0.021$).

The foliar N:P ratio increased with rate of N application. Values of 10 – 15 were reached sooner at higher than lower rates of N-fertiliser application, and by age 17 months, N:P of all treatments was within this range (Table 8.14). However, by age 24 months N:P ratios of the two highest N fertiliser rates (N₈₀₀ and N₁₂₀₀) were below 10.

8.3.4 *E. globulus* foliar nutrition and diameter growth

There was a significant and strong relationship between diameter increment (D_{inc}) between 7 – 11 months and foliar N concentration at age seven months ($p < 0.001$; $r^2 = 0.58$) (Figure 8.10a). The relationship with N content (mg leaf^{-1}) was poorer ($p = 0.006$; $r^2 = 0.38$) (data not shown) as were relationships between D_{inc} and P concentration (%) or P content (mg leaf^{-1}) (data not shown). The relationship between D_{inc} (ages 12 – 17 months) and foliar N concentration at age 13 months was weak (one month after the second fertiliser application) ($p = 0.082$; $r^2 = 0.09$), however, N content (mg N leaf^{-1}) at 13 months had a stronger relationship ($p < 0.001$; $r^2 = 0.49$) (Figure 8.10b). At this age the relationship for foliar P concentration was not strong, but the relationship with P content was significant ($p < 0.001$; $r^2 = 0.44$) (data not shown).

The relationships between D_{inc} and foliar concentration or content in experiment 1 was strongly controlled in two distinct groups defined by W and WF conditions. D_{inc} in W treatments was < 0.15 cm for N concentration of 1.2 – 2.4%, while D_{inc} for WF treatments ranged from 0.23 – 0.74 cm for concentrations from 2.1 – 3.1 % (Figure 8.10a). In Figure 8.10b, D_{inc} of W treatments was < 0.5 cm within a wide range of N contents, except for two N_{High} plots (circled), which had relatively higher surface soil

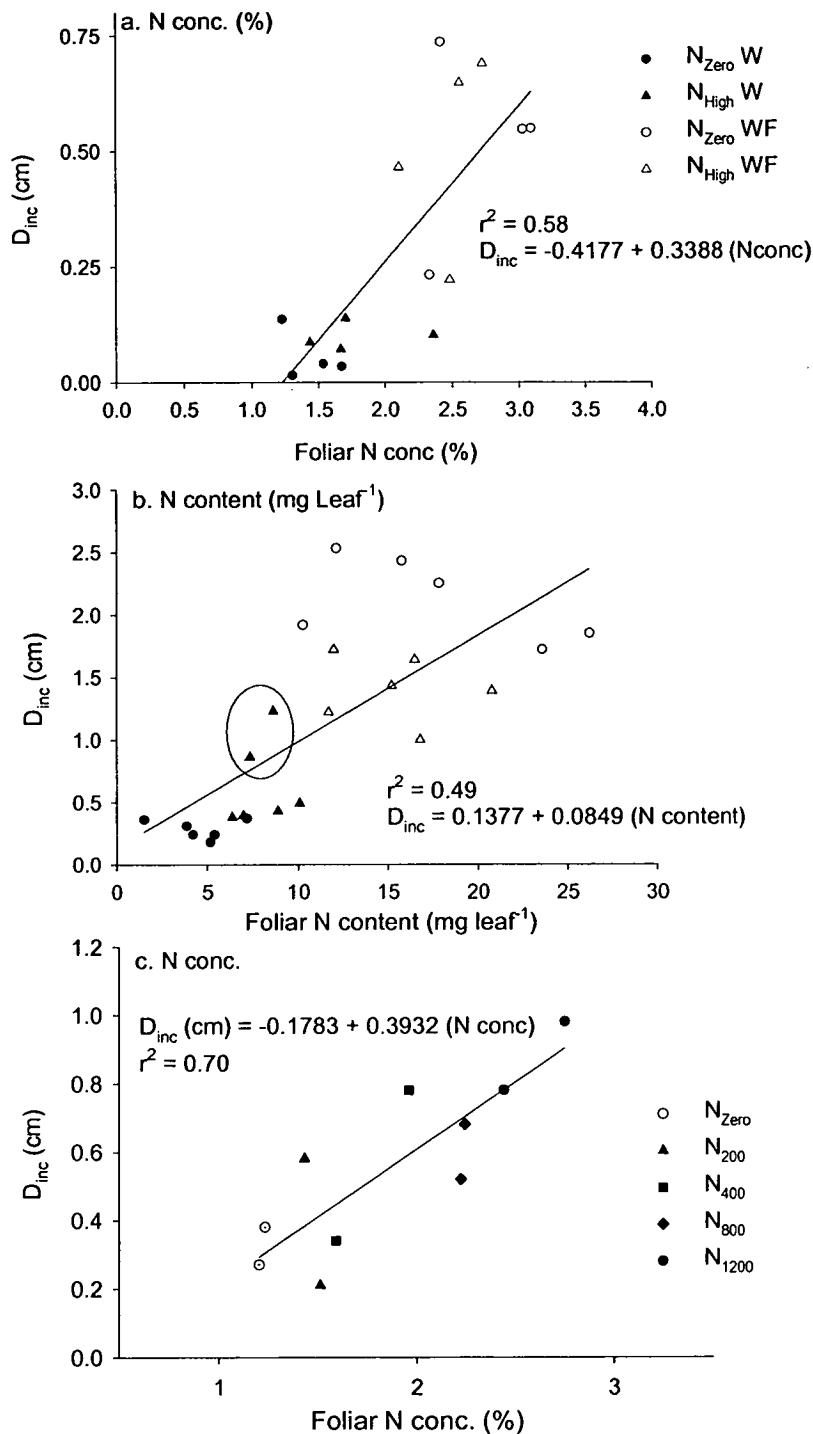


Figure 8.10 Foliar nutrient relationship to diameter increment (D_{inc}) (a) Experiment 1 N concentration (age 7 months) to D_{inc} (age 7 to 11 months) with two blocks and both levels of irrigation, (b) Experiment 1 N content (age 13 months) to D_{inc} (age 12 to 17 months) with three blocks and two levels of irrigation (the circle indicates the two N_{High} W plots that had higher sol surface water availability) (c) Experiment 2 N concentration (age 13 months) to D_{inc} (age 12 to 17 months) with two blocks and all N-fertiliser rate treatments.

water availability (Chapter 5 and 7). The relationship for WF treatments was more variable with concentrations ranging from 10 – 26 mg leaf⁻¹ and diameter increments from 1.0 – 2.5 cm.

In the N-fertiliser rate experiment, relationships between D_{inc} and foliar nutrition were strong at 13 months with both N concentration and N content related to increased D_{inc} with increasing rate of nitrogen applied ($p=0.003$; $r^2 = 0.70$ (Figure 8.10c) and $p<0.001$; $r^2 = 0.80$ respectively). However, such relationships were weaker on other occasions. There were no strong relationships between growth and foliar P, eg. one month after nitrogen fertilising (age 13 months), P concentration was unrelated to diameter increment.

The relationship between foliar N:P ratio (age 13 months) and diameter increment (12 – 17 months) in experiment 1, showed that the largest increments were associated with N: P ratios between 10 and 12 (Figure 8.11 a). Diameter increments were lower when ratios were greater or lower than this range. For this increment period, trees with ratios greater than 12 were those that had received N-fertiliser and were growing in weedy plots, while trees with lower ratios were those that were unfertilised in weedy plots. In the N-fertiliser rate experiment for the same period (12 – 17 months) the highest diameter increments were also associated with N:P ratios of 12.

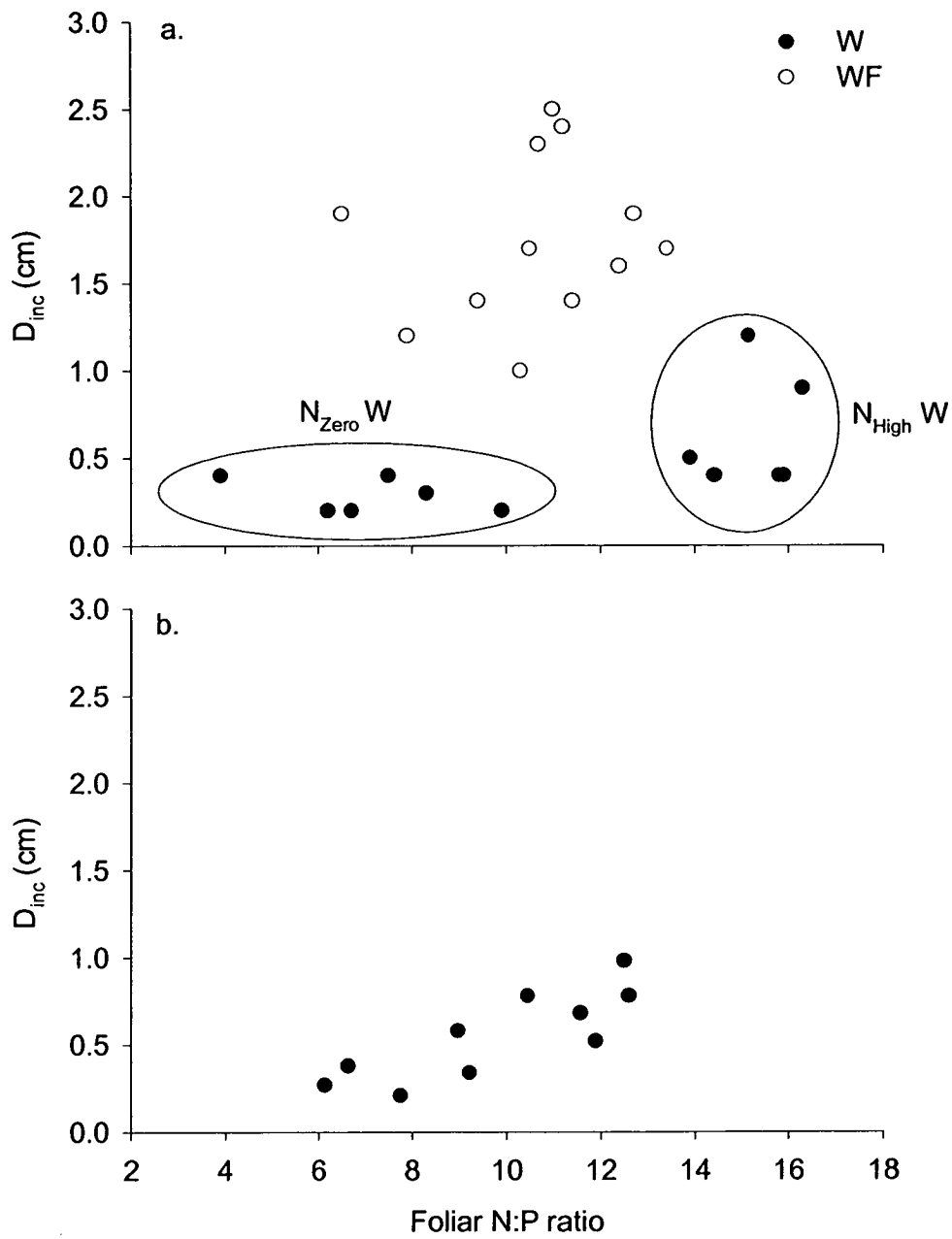


Figure 8.11 Foliar N:P ratio relationship to diameter increment (D_{inc}) (a) Experiment 1, N : P ratio (age 13 months) to D_{inc} (12 to 17 months) (b) Experiment 2, N:P ratio (age 13 months) to D_{inc} (12 to 17 months) for all N fertiliser rate treatments.

8.3.5 Vector analysis – *E. globulus* nutrition*Nitrogen*

Figure 8.12 illustrates vector diagrams for *E. globulus* N nutrition at age 7, 10, 13, 15, 17 and 20 months. Only significant effects and interactions have been plotted to simplify the diagrams, allowing easier interpretation. The analysis (ANOVA) of relative values for concentration, content and leaf mass showed the same significant treatments (interactions or main effects) as both nitrogen concentration and content (Table 8.15). The exception was at tree age 15 and 17 months where both Nitrogen and Weeds were significant main effects for relative N concentration (vector analysis), compared to Nitrogen alone at age 15 months and Weeds alone at age 17 months (N concentration).

Table 8.15 List of significant main effects and interactions and LSD's for N concentration and N content alone compared with results for relative N concentration and relative N content

Sample date (months)	N Conc LSD		Vectors		N Content LSD		Vectors	
			Relative Conc	LSD			Relative Content	LSD
7	W	0.4592	W	0.3370	W	6.530	W	1.4020
10	N x W	0.4112	N x W	0.2428	N, W	1.596	N, W	0.2752
13	N x W	0.5199	N x W	0.2807	W	2.957	W	0.5950
15	N	0.2870	N, W	0.1310	N x W	5.141	N x W	0.6400
17	W	0.2768	N, W	0.1416	N, W	3.740	N, W	0.4720
20	N, W	0.1368	N, W	0.0557	I x N x W	9.770	I x N x W	1.0720

At age seven months, the significant main effect was due to weed presence ($p=0.002$ and $p=0.032$ for N concentration and N content respectively). Weed-free treatments had significantly higher N concentration, N content and leaf mass than W treatments. The vector direction indicates a C shift, suggesting that the W treatments were experiencing an N deficiency (Figure 8.12).

At age ten months, a significant second order nitrogen x weeds interaction for N concentration was present ($p=0.004$), where relative changes in N concentration were higher for all WF treatments and the N_{High} W treatments, compared to N_{Zero} W treatments. N content was also significantly greater for these treatments ($p<0.001$). A vector C shift (deficiency) was still indicated (Figure 8.12).

These trends continued at age 13 months (one month following the second N fertiliser application), with significantly higher N concentration in WF and N_{High} W treatments compared to N_{Zero} W. At this age however, N content was not significantly greater in N_{High} W treatments than N_{Zero} W treatments, which is interpreted as a D shift, or luxury uptake (no change in mass but increase in concentration and content).

At age 15 months, the differences between WF and W treatments for N content were getting larger while the N concentration difference was reducing (still significantly higher in N-fertilised treatments). The vector shift for WF treatments was approaching a B shift, suggesting a sufficiency status for N content. Meanwhile, N_{High} W treatments still indicated a deficiency shift compared to N_{Zero} W treatments for both N concentration and N content (Figure 8.12).

At age 17 months, the significant main effect was due to weed presence with both N concentration and N content significantly higher in WF treatments ($p=0.004$ and $p<0.001$ for N concentration and N content respectively). A vector shift in the B direction was still apparent, again suggesting that WF treatments had sufficient status.

By age 20 months (two months after the third N-fertiliser application) a significant third order water x nitrogen x weeds interaction was present for N content ($p=0.021$). Unfertilised WF treatments receiving I_{Low} had higher N content than I_{High} or N_{High} WF treatments. Weed presence and nitrogen treatment were significant for N concentration ($p=0.008$ and $p<0.001$ respectively). Sufficiency status for N concentration and N content was clearly indicated for WF treatments, while N_{High} W treatments continued to indicate deficiency.

Phosphorus

Vector analysis confirmed that P was generally sufficient throughout all treatments but with much higher content and leaf mass in WF than W treatments (data not shown). At age 10 months WF treatments receiving I_{Low} had a trajectory that indicated a deficiency rather than sufficiency. Weedy treatments were more variable with concentration and content not significantly different from each other.

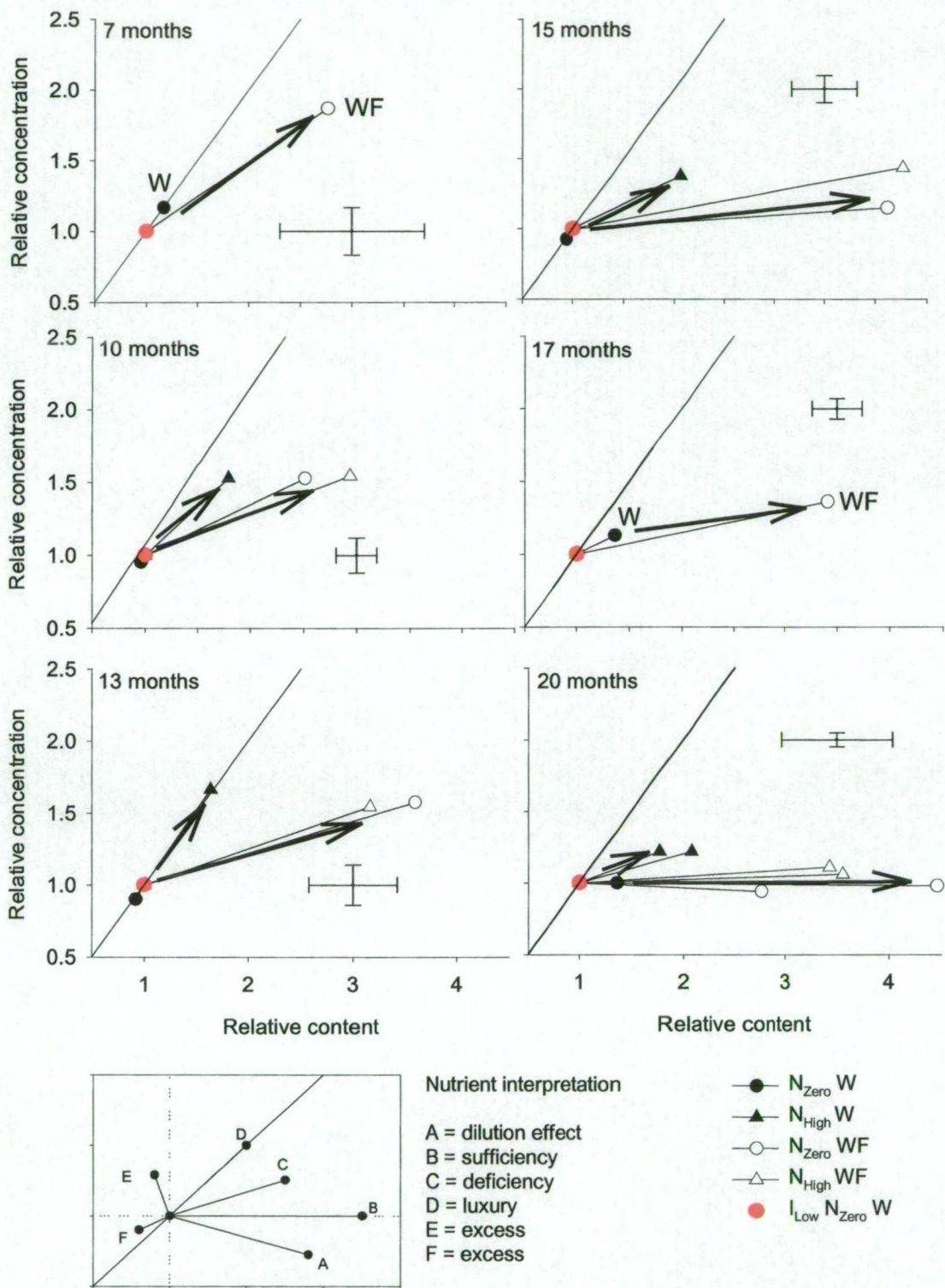


Figure 8.12 *E. globulus* Vector analysis of the effect of water, nitrogen and weed treatments on foliar N concentration and leaf content (experiment 1). Relative leaf mass is also indicated. The solid line depicts unchanged mass ($I_{Low} N_{Zero} W$). Bi-directional error bars are LSD ($p=0.05$) for N concentration (vertical) and N content (horizontal) for comparing main effects or interactions. Arrows indicate vector shifts. The red point indicates the reference or control ($I_{Low} N_{Zero} W$).

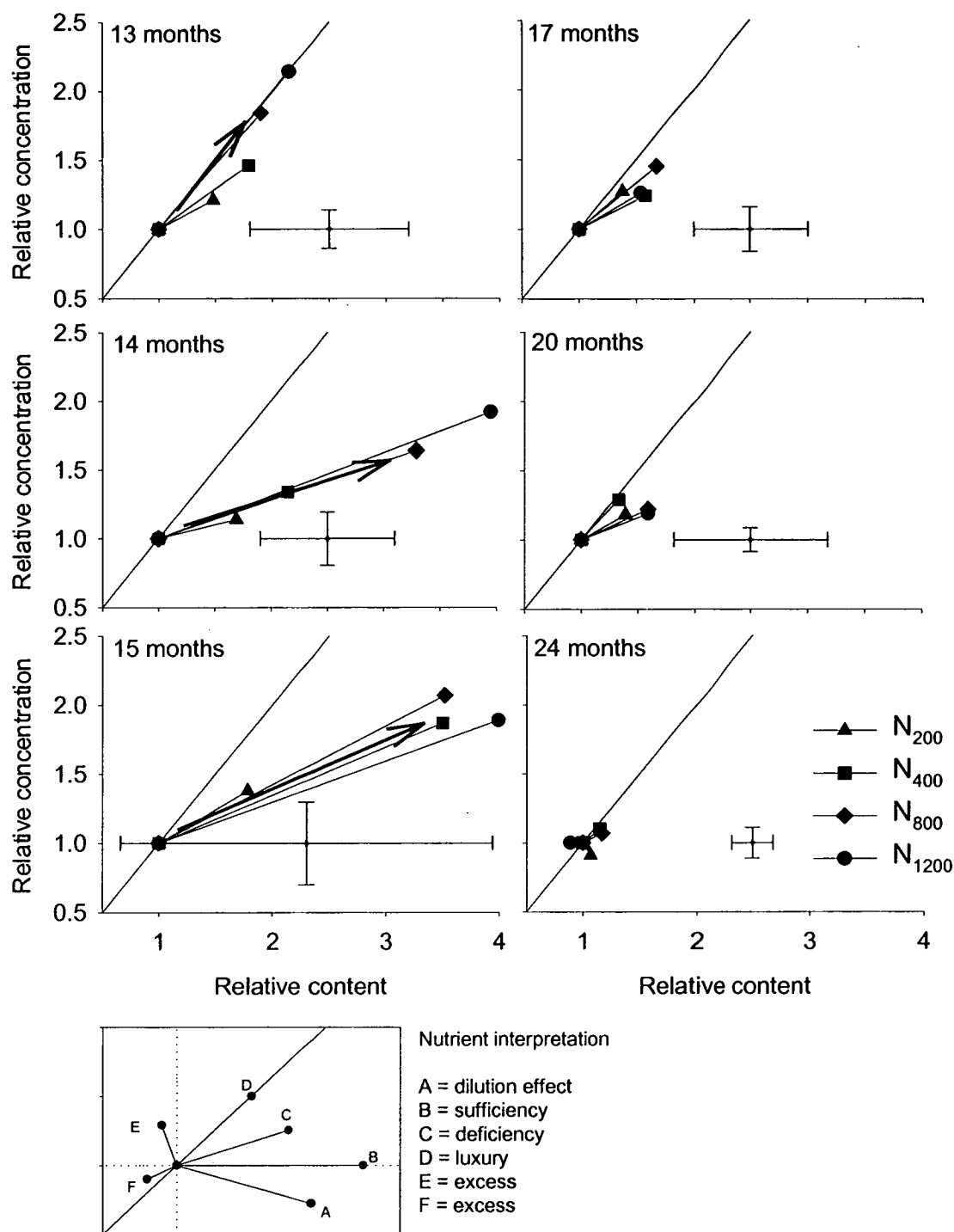


Figure 8.13 *E. globulus* Vector analysis of the effect of N fertiliser rate on foliar N concentration and leaf content (experiment 2). The reference is N₀. Bi-directional error bars are LSD (p=0.05) for N concentration (vertical) and N content (horizontal) for comparing main effects.

At age 13 months, an antagonistic response (shift F) was indicated for all W treatments, suggesting that some other factor was involved. At age 15 and 17 months all treatments indicated sufficiency while at age 20 months N_{High} W treatments indicated deficiency. The remaining treatments were sufficient in P (data not shown). The general trend for W treatments suggested a dilution before age 15 months, then sufficiency, while a deficiency was indicated at age 20 months.

Nitrogen rate experiment

In W treatments receiving I_{High} , the highest *E. globulus* foliar N concentrations and content tended to occur with the highest N-fertiliser rates (Figure 8.13). At age 13 months luxury uptake was indicated in N_{800} and N_{1200} treatments (these treatments had received 400 and 600 kg N ha⁻¹, respectively), while N_{400} indicated a C shift (deficiency)(20 kg N ha⁻¹ applied). Foliar N concentration or N content for N_{200} was not significantly different from the N_0 treatment. By age 14 months all N-fertilised treatments were indicating deficiency (Shift C) with significant differences between treatments. However, differences between treatments became smaller over time as the control treatment (N_0) increased nutrient status. From 17 - 24 months there were no significant differences between treatments for content or concentration.

There were no significant differences between P concentrations for treatments until age 20 months, with most vector trajectories indicating sufficiency (Shift B) (data not shown). The highest P content was associated with the highest N-fertiliser rate. The N_{200} and N_{400} treatments indicated P deficiency (Shift C) throughout the experiment, while the N_{800} and N_{1200} treatments initially indicated luxury uptake (Shift D) but

then deficiency (Shift C). The greatest relative differences occurred during the first few months after the November 1997 application of fertiliser.

8.3.6 N and P status of *H. lanatus*

The concentration of N in *H. lanatus* shoots ranged from 1.1 – 2.3 % during the three harvest dates (July 1997, November 1997 and March 1998), for both live and dead biomass (Table 8.16). Concentrations of N in N_{High} treatments were up to double those in N_{Zero} treatments ($p < 0.05$). A seasonal effect was apparent for the N_{Zero} treatments; N concentration was 1.3 % in July, declined to around 1% in November, then increased to 1.6% in March, when the proportion of live foliage was lowest. The concentration of N in dead biomass was approximately 1.9 % in the N_{High} treatment and 1.1% in the N_{Zero} treatment. Both were lower than the live grass at the same time ($p > 0.05$) (2.2 % and 1.6 % respectively). In contrast, the concentration of P in grass was relatively stable, with no significant differences between treatments and dates (Table 8.16). However, there was a trend for higher P concentrations in N_{High} treatments ($p > 0.05$).

Nutrient content, a function of concentration and biomass, varied by treatment, season and live or dead biomass. Fertilised grass contained significantly more N than N_{Zero} grass in July and November 1997, while in March 1998, no significant difference occurred (Table 8.16). In July, N_{Zero} grass contained 77 kg N ha⁻¹ compared to 193 kg N ha⁻¹ for N_{High} treatments, while in November the content increased to 90 kg N ha⁻¹ and 287 kg N ha⁻¹ respectively. There was also an irrigation by nitrogen interaction ($p = 0.040$). Fertilised grass receiving I_{High} contained 15% less N than grass receiving I_{Low} (264 and 310 kg N ha⁻¹ respectively). In

contrast, N_{Zero} grass receiving I_{High} had 37% more N than grass receiving I_{Low} (104 and 76 kg N ha⁻¹ respectively). In March 1998, the live biomass was low and there was no significant difference in N content between treatments. For dead biomass, N content varied between 64 – 139 kg N ha⁻¹, and was least in $I_{High} N_{High}$ treatments ($p>0.05$).

Table 8.16 Grass nutrient concentration (%) and content (kg ha⁻¹)

Date	Status	Treatment	Concentration (%)				Content (kg ha ⁻¹)			
			N		P		N		P	
Jul-97	Live	$I_{Low} N_{Zero}$	1.35	a	0.24	a	81.0	a	14.3	a
		$I_{Low} N_{High}$	2.07	b	0.29	a	197.0	b	27.8	b
		$I_{High} N_{Zero}$	1.24	a	0.26	a	74.0	a	15.1	a
		$I_{High} N_{High}$	2.08	b	0.29	a	189.0	b	26.1	ab
Nov-97	Live	$I_{Low} N_{Zero}$	0.90	a	0.19	a	76.5	a	16.5	a
		$I_{Low} N_{High}$	2.19	b	0.22	a	310.5	b	31.9	b
		$I_{High} N_{Zero}$	1.07	a	0.22	a	104.0	a	21.8	a
		$I_{High} N_{High}$	1.89	b	0.23	a	264.3	b	32.7	b
Mar-98	Live	$I_{Low} N_{Zero}$	1.60	a	0.25	a	22.9	a	3.6	a
		$I_{Low} N_{High}$	2.33	b	0.22	a	41.8	a	3.8	a
		$I_{High} N_{Zero}$	1.58	a	0.24	a	35.0	a	5.3	a
		$I_{High} N_{High}$	2.05	ab	0.22	a	27.9	a	2.9	a
Mar-98	Dead	$I_{Low} N_{Zero}$	1.12	a	0.18	a	100.0	a	15.9	a
		$I_{Low} N_{High}$	1.85	b	0.21	a	139.0	a	14.5	a
		$I_{High} N_{Zero}$	1.10	a	0.18	a	111.0	a	18.2	a
		$I_{High} N_{High}$	1.90	b	0.23	a	64.0	a	6.9	a

Within each date, and nutrient, treatments appended by the same letter are not significantly different ($p<0.05$). There was an irrigation by nitrogen interaction in November 1997 applying to N content.

P content behaved similarly to N. There was approximately twice the P content in N_{High} compared to N_{Zero} grass during July and November 1997 (16 kg P and 32 kg P

ha⁻¹ respectively). In March 1998 P content was low, 3 – 5 and 7 – 16 kg P ha⁻¹ for live and dead biomass respectively (Table 8.16).

H. lanatus N and P status indicated increasing concentrations, content and mass due to N-fertiliser. Vector analysis of the data in July 1997, indicated a C shift or deficiency response (data not shown). In N_{High} grass, N concentration and content was significantly greater, and P content was significantly greater than in N_{Zero} grass. Increased growth brought about by N-fertiliser application enhanced P concentration and content. All other treatments were not significantly different from the control. The magnitude of the vectors in July and November indicated that nitrogen was the most important nutrient limiting grass growth at this site.

8.3.7 Vector competition analysis - *E. globulus* competing with *H. lanatus*

Vector competition analysis was carried out on age 10, 13 and 17 month data. At age 10 months, I_{Low} N_{Zero} treatments indicated there was no relative change in grass response (indicated by no change in biomass, N or P content), while the *E. globulus* seedlings were negatively affected (as indicated by a strong decline in relative biomass and N and P content) (Figure 8.14a). Nitrogen and P content declined more than leaf mass relative to the control. Such a response is defined as antagonistic dilution or competition for nutrients (Figure 8.2) and this did not alter under I_{High} (Figure 8.14b). These nutrient competition trends were also indicated at age 13 and 17 months (data not shown). Where N-fertiliser was applied at age 10 months (Figure 8.14c), a vector B shift (compensatory) indicated a positive grass response and a negative tree response in relation to the respective controls. Table 8.17 shows the interpretation of this as a deficiency in both N and P for grass in N_{High} treatments

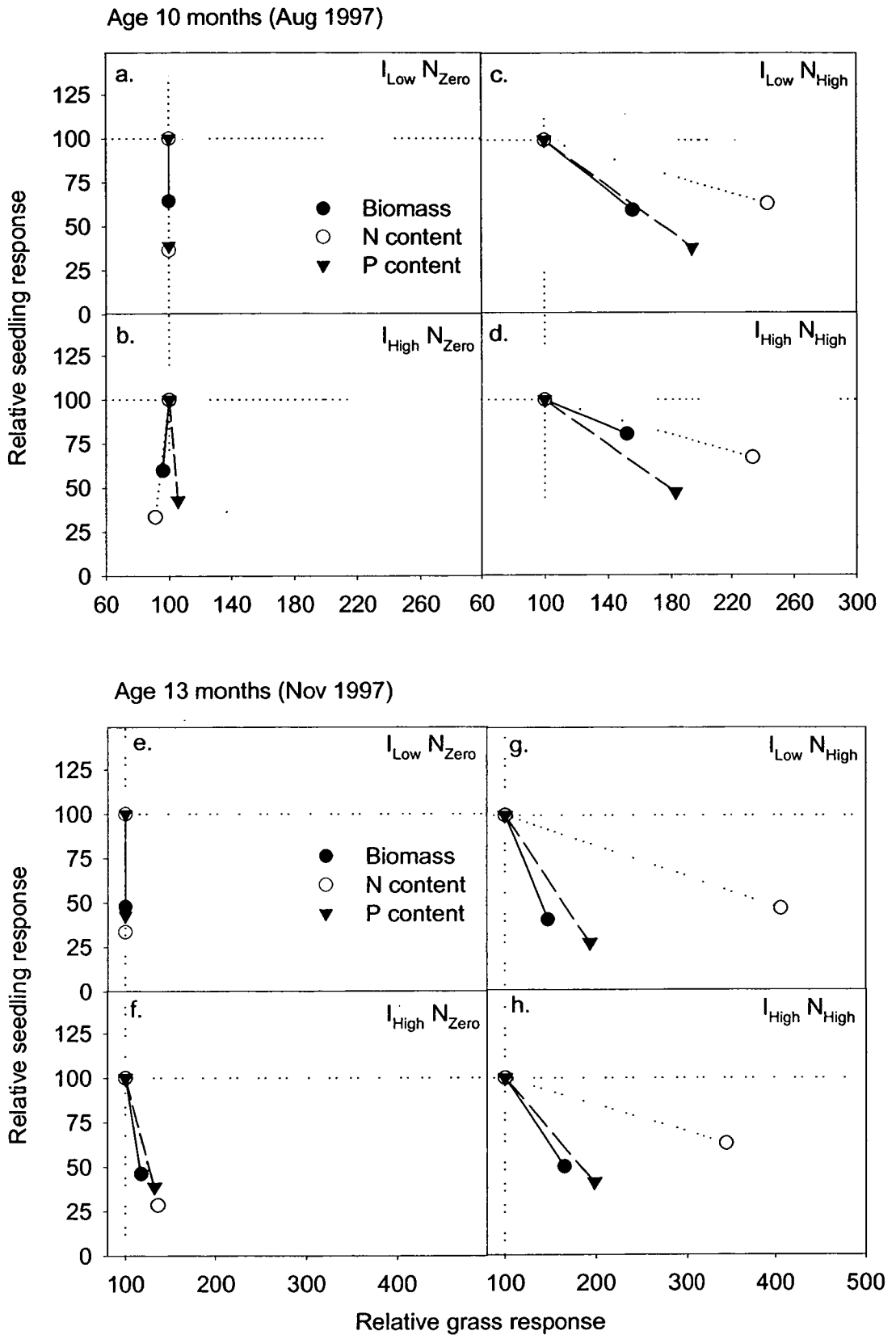


Figure 8.14 Vector competition analysis of relative biomass and nutrient uptake (content) in W treatments at age 10 months and age 13 months. *E. globulus* responses were normalised to $I_{Low} N_{Zero}$ WF (=100) and *H. lanatus* was normalised to $I_{Low} N_{Zero}$ W (= 100).

Table 8.17 Table summarising vector shifts and interpretations for vector competition analysis.

Nitrogen									Phosphorus					
Months	Species	Treatment	Ratio		Relative change		Diagnosis	Possible interactions	Ratio		Relative change		Diagnosis	Possible interactions
			N	Biomass	N	P			Biomass	P				
10	Grass	I _{Low} N _{High} W	1.6	+	+	Def	Improved N avail	1.2	+	+	Def	Improved N avail		
Aug 97	Grass	I _{High} N _{Zero} W	1.0	= / -	= / -	Suff / Def	Improved N, water avail	1.1	= / -	= / -	Excess uptake	Other competition		
	Grass	I _{High} N _{High} W	1.5	+	+	Def	Improved N avail	1.2	+	+	Def	Improved N avail		
	Trees	I _{Low} N _{Zero} W	0.6	-	-	Ant dilution	Nutrient competition	0.6	-	-	Ant dilution	Nutrient competition		
	Trees	I _{Low} N _{High} W	1.1	-	-	Excess uptake	Other competition	0.6	-	-	Ant dilution	Nutrient competition		
	Trees	I _{High} N _{Zero} W	0.6	-	-	Ant dilution	Nutrient competition	0.7	-	-	Ant dilution	Nutrient competition		
	Trees	I _{High} N _{High} W	0.8	-	-	Ant dilution	Nutrient competition	0.6	-	-	Ant dilution	Nutrient competition		
13	Grass	I _{Low} N _{High} W	2.8	+	+	Def	Improved N avail	1.3	+	+	Def	Improved N avail		
Nov 97	Grass	I _{High} N _{Zero} W	1.2	+	+	Def	Improved N avail	1.1	+	+	Def	Improved N avail		
	Grass	I _{High} N _{High} W	2.1	+	+	Def	Improved N avail	1.2	+	+	Def	Improved N avail		
	Trees	I _{Low} N _{Zero} W	0.7	-	-	Ant dilution	Nutrient competition	0.9	-	-	Ant dilution	Nutrient competition		
	Trees	I _{Low} N _{High} W	1.2	-	-	Excess uptake	Other competition	0.7	-	-	Ant dilution	Nutrient competition		
	Trees	I _{High} N _{Zero} W	0.6	-	-	Ant dilution	Nutrient competition	0.8	-	-	Ant dilution	Nutrient competition		
	Trees	I _{High} N _{High} W	1.3	-	-	Excess uptake	Other competition	0.8	-	-	Ant dilution	Nutrient competition		
17	Grass	I _{Low} N _{High} W	1.4	+	+	Def	Improved N avail	0.8	+	= / +	Growth dil	Improved other avail		
Mar 98	Grass	I _{High} N _{Zero} W	1.0	+	+	Sufficiency	Improved N, water avail	1.0	+	+	Sufficiency	Improved N, water avail		
	Grass	I _{High} N _{High} W	1.3	-	+	Excess uptake	Other competition	0.9	-	-	Ant dilution	Nutrient competition		
	Trees	I _{Low} N _{Zero} W	0.7	-	-	Ant dilution	Nutrient competition	0.8	-	-	Ant dilution	Nutrient competition		
	Trees	I _{Low} N _{High} W	0.9	-	-	Ant dilution	Nutrient competition	0.8	-	-	Ant dilution	Nutrient competition		
	Trees	I _{High} N _{Zero} W	0.8	-	-	Ant dilution	Nutrient competition	0.9	-	-	Ant dilution	Nutrient competition		
	Trees	I _{High} N _{High} W	0.9	-	-	Ant dilution	Nutrient competition	0.9	-	-	Ant dilution	Nutrient competition		

Ant = antagonistic, Def = deficient, Suff = sufficient

(improved nutrient availability by fertilising) and no change or sufficient in N_{Zero} treatments. The majority of *E. globulus* responses were defined as antagonistic dilution (nutrient competition). The $I_{Low} N_{High}$ treatments indicated there may have been excess uptake by *E. globulus* (increased N uptake while relative change in biomass decreased). This suggests that growth was constrained by some other factor.

At age 13 months, compensatory shift B vectors indicated deficiency for N and P of grass in the N_{High} treatments (N availability increased) and a response to the I_{High} treatment (indicating some limitation). *E. globulus* showed antagonistic dilution (Table 8.17), indicating competition for nutrients, except in the two N_{High} treatments (Figure 8.14f,g), where it appeared that excess uptake was occurring, again suggesting that some other limiting factor was also involved.

At age 17 months different vector shifts for grass were apparent (data not shown). In all cases, trees showed antagonistic dilution (or competition for nutrients), while grass showed sufficiency for both N and P in the $I_{High} N_{Zero}$ treatment. Under $I_{Low} N_{High}$, grass vectors indicated an N deficiency and a P dilution effect. The $I_{High} N_{High}$ treatment, indicated that the relationship between grass and trees was antagonism for both N and P. This was expressed as excess uptake of N by grass and antagonistic dilution for P, including a slight decrease in growth (Table 8.17).

8.4 Discussion

The foliar nitrogen status of *E. globulus* was significantly reduced in the presence of *H. lanatus* during the first 18 months of growth. This result is consistent with the findings of many other studies that have considered competition between weeds and

trees for N (Ellis *et al.* 1985, Smethurst and Nambiar 1989, Woods *et al.* 1992, Morris *et al.* 1993, Caldwell *et al.* 1995, Nilsson *et al.* 1996). Therefore, direct competition between grass and young *E. globulus* for mineral N has been an important factor during the establishment of the tree seedlings from at least age five months until age 18 months. The high demand for and uptake of mineral N by grass reduced the availability of this resource to the young trees (Chapter 7) and was reflected in significantly lower *E. globulus* foliar N concentration and N content.

For one- to two-year-old *E. globulus*, N deficiency has been defined as 1 – 1.7% N and adequacy as 2.5 – 2.8 % N (Dell *et al.* 1995). Boardman *et al.* (1997) proposed similar ranges (deficiency < 1% N, and adequacy 2 – 2.8% N). Shedley *et al.* (1995) suggested a range of critical N concentration between 2.4 – 2.9 % across various N forms. These ranges are comparable with those for other species: *E. saligna* 2.25 – 2.94% (Yost *et al.* 1987) and *E. fastigata* (2.34%) (Knight 1988); but are higher than those reported for *E. grandis* (Shönau and Herbert 1982). Concentration ranges have also been suggested for P, with deficiency defined as < 0.1% P and adequacy between 0.14 and 0.26% P (Boardman *et al.* 1997). Neilsen (1996) suggests that the optimum N concentration for a related species, *E. nitens* was 2%, while P was 0.16%. Concentration ranges have been suggested for K, with deficiency defined as < 0.4% K and adequacy between 0.8 and 1.2% K (Boardman *et al.* 1997). Foliar Na concentrations that are considered to be toxic have been suggested as > 1% (Lambert and Turner 2000). These differences in ranges indicate the difficulty of determining critical concentrations across a wide range of conditions.

In the present study, foliar N concentrations of *E. globulus* in WF treatments, where there was no competition for N, were in the adequate range 2.5 – 2.8% at seven months, but those of N_{Zero} W treatments were in the deficiency range (1 % – 1.7 %; Dell *et al.* 1995). These N_{Zero} W trees had small, chlorotic leaves and stunted growth, especially during the first year of growth. Phosphorus concentrations did decline over time and during 15 – 17 months W treatments approached the bottom of the adequate range (Dell *et al.* 1995). Therefore the possibility of a P deficiency should not be excluded. In WF treatments foliar N and P remained above the deficiency level from age five months, indicating access to sufficient N and P in the absence of weeds (Dell *et al.* 1995, Boardman *et al.* 1997). Nitrogen concentrations across treatments did not exceed 3.1% despite high rates of N-fertiliser application (900 kg N ha⁻¹ and 1200 kg N ha⁻¹ for experiment 1 and 2 respectively) which is consistent with many *E. globulus* nutrition studies (cited by Cromer 1995).

Where N fertiliser was applied in W treatments (N_{High} W), rapid increases in *E. globulus* foliar N concentrations occurred, which by age 10 months were equivalent to those in WF treatments (Figure 8.3a). The largest foliar N concentration increases occurred after the application of 300 kg N ha⁻¹ at age 12 months. Where rates lower than 200 kg N ha⁻¹ were applied, the grass appeared to be able to capture most of it, with little left over for the trees. Vigorous young *E. globulus* can utilise greater than 100 kg N ha⁻¹ during the first year of growth (Cromer 1996). However, in weedy conditions, grass weeds often benefit proportionately more than trees from N-fertiliser application (Squire 1977, Boomsma and Hunter 1990, Woods *et al.* 1992). For example, Squire (1977) found that grass growth was stimulated by N-fertiliser application to young *P. radiata* and the

benefits to tree growth of the applied N (224 kg N ha^{-1}) were effectively negated. In the current study, high nutrient uptake rates by *H. lanatus* were clearly demonstrated where N_{High} grass had double the N concentration of N_{Zero} grass (2% compared to 1%) and above-ground N content was up to four times higher (310 kg N ha^{-1} and 76 kg N ha^{-1} , respectively). Similar levels of N content have been reported for a pasture containing *H. lanatus* by Parfitt *et al.* (2003) (389 kg N ha^{-1}). The P concentration in *H. lanatus* in the current study was unchanged (0.22%) between treatments, but P content was almost double in N_{High} compared to N_{Zero} treatments at age 10 and 13 months.

In the N rate experiment, a decline in *E. globulus* nitrogen concentrations was apparent at age 13 – 14 months, which probably reflected increased demand from the grass as it approached seed set and maturity over summer. Soil water would also have been under high demand by grass at this time. In the drier Block 3, N_{High} grass had 90% lower plant available soil water during spring 1997, and matured four weeks sooner than slower growing N_{Zero} grass (Chapter 3 and Chapter 5). Where I_{High} was applied to N_{High} W treatments, the improved *E. globulus* foliar N concentration was temporarily increased (Figure 8.3a); suggesting that an increase in available soil water (via irrigation) increased the uptake of mineral N. Higher tree growth in these treatments compared to I_{Low} N_{High} W treatments (Chapter 4) also suggests that increased water availability enhanced leaf growth and water relations. At age 13 months in Block 3, leaf water potential measurements indicated that I_{Low} W treatments were moderately stressed ($\psi_{\text{max}} = -1.24 \text{ MPa}$) compared to I_{High} W treatments ($\psi_{\text{max}} = -0.60 \text{ MPa}$) (Chapter 6). However, the main effect of I_{High} in the longer term, was a reduction of foliar N concentrations compared to I_{Low} for both W

and WF treatments, at least until age 17 months. This is consistent with findings that leaching losses were high under I_{High} , reducing the availability of N for tree uptake (Chapter 7) but could also be related to water salinity levels.

Strong competition for K between grass and young *Pinus elliottii* has been reported on a spodosol in Florida (Smethurst *et al.* 1993) which showed that foliar K was significantly reduced in the presence of grass. In this study, *E. globulus* foliar K concentrations during the first 10 months of tree growth were within the range 0.58% – 0.92%, above concentrations considered to be deficient (Boardman *et al.* 1997). The highest concentrations occurred in weed-free treatments or those receiving low irrigation, and were within the adequate range (Boardman *et al.* 1997). This suggests that competition for K may have been a component of the grass – tree interaction.

The relationship between *E. globulus* growth and N concentration or N content ranged from weak to strong. In W treatments receiving I_{High} , *E. globulus* N concentrations increased with increasing N-fertiliser rate (up to 600 kg N ha⁻¹), applied at age 12 months, and led to increased diameter increment for a five-month period (12 – 17 months). Using this regression approach it was shown that 70% of the diameter increment for this period could be accounted for by N concentration at age 13 months. Foliar N concentration after 14 months provided weak predictors of diameter growth. This can be related back to the strong linear responses by N concentration (age 13 and 14 months) to rate of N applied (Figure 8.9). After this age the responses became non- linear which peaked at approximately 400 kg N ha⁻¹. By age 24 months the relationship between N concentration and N rates was weak across

all treatments. In experiment 1, the water and weed treatments as well as N fertiliser interacted to result in poor relationships between growth and N concentration or content. This is consistent with other studies where, especially beyond juvenile growth, factors in addition to nutrition (eg. water availability) have a large influence on tree growth (Judd *et al.* 1996b).

The difficulties in defining critical concentrations are that many factors can affect nutrient concentration (Bates 1971, Lamb 1976, Cromer and Williams 1982, Bell and Ward 1984, Leuning *et al.* 1991) and small differences in concentration around the critical value may lead to mis-interpretations. A given concentration also does not account for potential nutrient imbalances, which may be more important for tree nutrition (Linder 1995). Ratios have been widely used in South Africa, particularly for *E. grandis*, and appear to be very useful for nutritional management of this species (Herbert 1996). However, these techniques require extensive calibration and an underlying understanding of nutrient relationships, interactions and their physiological basis (Dell *et al.* 1995).

Nutrient ratios also require an optimum N concentration to be set for the species in question (Proe *et al.* 1999). In the present study, the maximum N:P ratios in WF and W treatments peaked at 13.3 and 11.6 respectively at age 17 months. Before age 17 months, the N:P ratio for trees growing in N_{Zero} W treatments was below 10, which suggests that a response to N could have been achieved (Cromer 1996), while the higher ratios in the N_{High} W treatments suggest that P may have been limiting (Cromer 1996). In addition, some other factor such as soil water stress may have been involved. For WF trees the N:P ratio declined to seven during winter (age 10

months) before increasing to 12 – 13 by age 17 months. This ratio is below 15, the ratio considered to be the optimum for *E. globulus* (Cromer *et al.* 1981) and *E. nitens* (Judd *et al.* 1996a). However, Pereira *et al.* (1994) suggest lower ratios (~ 12.5) were optimum in an intensive trial using irrigation and fertiliser treatments. Another study also found a similar ratio for *E. globulus* seedlings (Ericsson 1994; cited in Pereira *et al.* 1996). Results from this current study (eg. Figure 8.11a) and Judd *et al.* (1996a) suggest an optimum ratio of around 12 for juvenile foliage. The higher ratio of 15 – 16 is probably more appropriate at older ages (Cromer *et al.* 1981, Judd *et al.* 1996a).

Expressing nutrient composition in terms of content (mg leaf^{-1}) rather than concentration improved interpretation and better reflected nutrient uptake in the portion of the plant of interest (Armson 1973). In *P. radiata*, fascicle weight was a good indicator of tree growth and health, though it was not as sensitive as height and diameter measurements (Mead and Mansur 1993). In young eucalypts, large changes in leaf size can occur during the juvenile phase (1-3 years in *E. globulus*) and as shown in this study, provided a good expression of differences between treatments. Thus N content (mg leaf^{-1}) of *E. globulus* in N_{High} W treatments was approximately double that of N_{Zero} trees from age 10 months while trees in WF treatments had approximately four times greater N content than N_{Zero} trees in W treatments (20 and 4.9 mg leaf^{-1} respectively). Foliar concentrations suggested that competition for N had declined by age 17 – 20 months, although N content showed continuing effects of competition that were associated with low growth rates beyond this age. In N_{Zero} W treatments, suppressed growth of *E. globulus* at age 20 months showed that N content had not reached the levels seen in WF treatments. Table 8.17 summarises the interpretations for the range of foliar analysis methods.

An alternative to examining nutrient concentrations or contents individually is to plot the changes in both, along with leaf mass, using vector analysis (Haase and Rose 1995). This method can be a very useful visualisation of treatment effects on tree growth and nutrition (Proe *et al.* 1999). In this present study, vector analysis improved insight into the weed – tree interaction and provided useful information linking concentration, content and growth (leaf mass). Evidence from this method was that *E. globulus* growth responses due to weed control were likely to be related to changes in nutrient supply during the first two years of growth. These results support results from the ‘traditional’ analysis methods (foliar N concentration and N content) (Table 8.17). However, evidence also suggested that N deficiency (competition for nitrogen) in N_{Zero} W treatments continued beyond 20 months of age. This was longer than that suggested by foliar N concentration analysis, but similar to N content. An extension of the vector analysis method: vector competition analysis (Imo and Timmer 1999), involving both the grass and trees together, indicated that competition between *H. lanatus* and *E. globulus* for N occurred at 10, 13 and 17 months. This result also supports the contention that competition between these two species was continuing well beyond age 18 months.

In contrast to nitrogen, results for phosphorus differed between the ‘traditional’ and vector methods (Table 8.17). The P concentration and N:P ratio method suggest P sufficiency throughout the study period, except for age 15 – 17 months when P concentrations declined towards the critical value. Results from vector analysis for the first year of growth (13 months) suggested that excess P was available for the trees, followed by sufficiency from 15 – 17 months. However, evidence suggests that P became limiting or deficient from age 20 months. In contrast, vector competition

analysis suggested that P deficiency commenced much earlier (age 10 months) and extended through to age 17 months. This differing result between methods for P status is difficult to explain, however, it is recognised that vector analysis requires accurate measures of growth response to link to the changes in concentration and content. Improved examination of the competitive effect of weeds on *E. globulus* could have been obtained if *E. globulus* nutrient contents of the whole tree crowns, rather than individual leaf mass, as used in this study. This is also the case for vector competition analysis.

Vector analysis also indicated that factors other than nutrients may have been involved in the grass – tree interaction in this study at different times. In a low rainfall environment, Mead and Mansur (1993) determined that soil moisture, in addition to nitrogen and boron, played an important role in the grass – tree interaction. In the present study, luxury uptake was indicated at age 13 months (soon after the application of 300 kg N ha⁻¹) which preceded leaf mass increases at age 15 months. Luxury uptake was not evident at age 20 months (two months following application of 300 kg N ha⁻¹). This luxury N uptake by *E. globulus* in N_{High} W treatments suggests that factors other than mineral N availability may have been more important at this time. It may also reflect the delay involved before young trees can fully utilise increased N availability. P and moisture are possible factors. Vector competition analysis also suggested that where N fertiliser was applied, some other limitation was occurring at 10 and later at 13 months. Again weed induced water stress may have been part of this interaction at age 10 and 13 months and P is also implicated.

The above discussion illustrates the usefulness of vector analysis as a method of interpreting treatment effects on tree growth and nutrition. However, there are also limitations to the use of this method and some difficulties associated with interpretation. Proe *et al.* (1999) in a study in Sitka spruce (*Picea sitchensis*) showed that outcomes from vector analysis are very sensitive to the test statistic selected for comparison of treatments. The boundaries between vector shifts depend on the direction of change and level of significance of foliar concentrations (Proe *et al.* 1999). These authors also showed that the standardised comparison claim should be questioned as they found different interpretations of vector analysis results depending upon where in the crown, the foliar samples were collected from (different canopy positions). Effects of harvest residue treatments were less in older foliage. If the error surrounding the control treatment is high then the associated error for the remaining treatments will be high when the relative values or ratios are calculated. This could lead to bias, and highly variable vectors that may not accurately present the real differences between treatments.

Apart from the original study (Timmer and Stone 1978) the majority of subsequent studies presenting vector analysis did not present error bars on vector diagrams, thereby making interpretation of treatment differences less conclusive. Many of these later studies present several nutrients on one vector diagram, which may have complicated the presentation of statistical significance but does not obviate the need for it. In the present study, analysis of the relative changes in N concentration and content (ANOVA) and presentation of bi-directional LSD's in the vector diagrams, along with presentation of only vectors that contained at least one significant change; ie. concentration and / or content, improved visualisation of the diagrams and

indicated the statistical significance of the various treatments depicted. It is considered a useful improvement to the presentation of vector diagrams, as depicted in this study where there were highly significant interactions or main effects (eg. nitrogen, weeds). Further work is needed to test its validity with other data sets and conditions.

The limitations of vector analysis methods mentioned above are acknowledged and care is needed when making interpretations from these methods. It is important to have suitable treatments available for comparison, and an adequate number of replications to minimise treatment variation. However, despite these limitations and concerns the two vector analysis methods have provided useful visualisation of treatment effects and enabled interpretation and determination of a range of responses that included luxury uptake, dilution and deficiency. When these are corroborated by other evidence from 'traditional' methods useful conclusions can be made.

Table 8.17 Comparison of analysis methods for nitrogen and phosphorus nutrition status (Experiment 1)

Method	Nitrogen							Interpretation
	Tree age (months) ⁽¹⁾							
	7	11	13	15	17	21	24	
Diameter growth response	suff ⁽²⁾	suff ⁽²⁾	def	def	def	def	def ⁽³⁾	Treatment differences suggest N deficiency from 13 - 20 months. ⁽²⁾ Sufficiency may have been deficient. ⁽³⁾ deficiency tending towards sufficiency at 24 months.
Foliar N concentration	def	def	def	def	def	suff		Deficient from 7 - 17 months, then sufficient.
Foliar N: P ratio	def	def	def	suff	suff	suff		Deficient from 7 - 13 months, then sufficient.
Vector Analysis	def	def	lux	def	def	suff / def		Deficient from 7 - 20 months, except 13 months when luxury uptake
Vector Competition Analysis		def	def		def			Antagonistic dilution or competition for N at 10, 13 and 17 months
	Phosphorus							
Foliar P concentration	suff	suff	suff	suff ⁽⁴⁾	suff ⁽⁴⁾	suff		Sufficient from 7 – 20 months, however ⁽⁴⁾ at 15 – 17 months concentrations approached deficiency levels.
Foliar N: P ratio	suff	suff	suff	suff	suff	suff		Sufficient from 7 – 20 months.
Vector Analysis	exc	dil	exc	suff	suff	def		Excess then dilution through to sufficient at 15 – 17 months. Deficient at 20 months.
Vector Competition Analysis		def	def		def			Antagonistic dilution or competition for P at 10, 13 and 17 months

(1) Age of tree growth measurements (approximate for other methods)

suff = sufficient, def = deficient, lux = luxury uptake, dil = diluted, exc = excessive uptake

8.5 Conclusions

It has been found that there was strong competition for N from an early age, that this significantly reduced tree growth in the presence of weeds, as reflected in lower N concentration and content, and growth in W treatments compared to WF treatments. These effects continued beyond two years of age. Foliar N concentration of *E. globulus* was significantly lower in W compared to WF treatments from age five to 17 months. During this period nitrogen deficiency was indicated in the W treatments with N concentration $< 2\%$ and slower growth. This period of deficiency corresponds with the critical period analysis (Chapter 4), which indicated that trees needed to be kept weed-free for the first 20 months after planting. After age 17 months, foliar N concentrations increased in N_{Zero} W treatments, and reached concentrations similar to WF trees by age 24 months. In comparison, significantly lower N content and leaf mass in W treatments continued through to age 24 months.

The growth and development of *H. lanatus* appeared largely unaffected by the presence of young *E. globulus* during the first two years of growth and benefited significantly more from the N-fertiliser application than the young trees. Nevertheless, nitrogen uptake by *E. globulus* in W treatments was enhanced by N-fertiliser application, with rapid increases in foliar N to apparently adequate levels, and equivalent to trees in WF treatments. Growth slowly increased over that of N_{Zero} W trees suggesting that the young trees were not able to fully utilise the increased N availability in the presence of the grass, until it had become morphologically and physiologically prepared, through the availability of other resources. In W treatments receiving I_{High}, *E. globulus* N concentrations increased with increasing N-fertiliser rate, and resulted in strong relationships between foliar N and diameter increment.

E. globulus foliar P concentrations were lower in all W treatments especially during the first year, although concentrations were not in the range considered to be deficient. However, from 15 – 17 months W treatments approached the bottom of the adequate range (Dell *et al.* 1995) and therefore the possibility of a P deficiency should not be excluded. Where high N-fertiliser rates were applied to W treatments, it was evident that *E. globulus* P concentrations were lower than in N_{Zero} W treatments. In addition, high foliar N:P ratios of N_{High} W treatments also suggest that P nutrition may have been limiting. There is evidence that K may also have been limiting growth in weedy treatments. Foliar Na concentrations were not considered to be within the toxic range.

Interpretation using N content and vector analysis, suggested that differences between W and WF treatments would have persisted for a period greater than 24 months, which was longer than the 18 months impact indicated by N concentration and critical period analysis. Vector analysis provided useful visualisation of treatment effects and trends in N status. Vector competition analysis, involving both the grass and trees together, provided improved insight into the weed-tree interaction. Ratios of N content: biomass indicated that factors other than N availability alone were restricting growth of *E. globulus* in the presence of grass at 10 and 13 months of age. Both water availability and P availability are implicated in this.

These two vector analysis methods have provided useful visualisation of treatment effects and have enabled interpretation and determination of a range of responses that included luxury uptake, dilution and deficiency. These interpretations are consistent with the growth responses of both trees and grass, resource availability and demands

at these times and will be examined and discussed further in Chapter 9 General discussion.

9. General discussion and conclusions

9.1 Introduction

E. globulus is very sensitive to below-ground competition from grass during establishment. Results from this study support the hypothesis that uptake of mineral N, and thus depletion of soil N availability by *H. lanatus*, has been a major competitive mechanism at this site. This is consistent with many other studies where a vigorous grass has been the dominant weed (Eissenstat and Mitchell 1983, Smethurst and Nambiar 1989, Neary *et al.* 1990, Reynolds *et al.* 2000, Robinson *et al.* 2002). Competition for soil water has been less important at this site due to the presence of a shallow water table (Blocks 1 and 2). However, weed-induced water stress did occur during the first year of growth in Block 3, where the water table was >2m. The timing, duration and importance of competition for nitrogen under various levels of water availability have been demonstrated. Using information from this study it is possible to predict the competitive interactions for soil water and nitrogen between grasses and young eucalypts at other sites.

The main findings from this study are that:

- *H. lanatus* caused strong growth suppression of young *E. globulus* (above- and below-ground) throughout the two years of growth;
- *H. lanatus* was a vigorous competitor for soil nitrogen within three months of planting the tree crop, and this continued to at least age 20 months;
- moderate competition for water occurred during the first year;
- soil water content affected nitrogen availability and uptake; and

- the timing and duration of below-ground competition was reflected in the critical period of weed control.

9.2 Suppression of *E. globulus*

E. globulus was strongly suppressed in the presence of the vigorous grass. Tree height and diameter growth was 48% and 60% smaller respectively in W compared to WF trees at age two years (Figure 4.2). Suppression occurred soon after planting in W treatments and there was no period during the first year when grass presence was tolerated by *E. globulus*. At age two years, tree height and diameter growth in W treatments indicated that growth was effectively 13 months behind WF trees at this age. There was also higher growth variability, and higher mortality in W compared to WF treatments, both sub-optimal outcomes for a plantation investment (Lewis and Ferguson 1993). Suppression of tree growth was greater in unfertilised grass treatments compared to N-fertilised treatments, especially where water was also limiting growth (eg. Block 3).

The time when grass becomes established at a site, relative to tree planting, influences the time when competition between the two species commences, and the importance of this competition (Tinker and Nye 2000). In general, suppression of tree growth increases as the duration of grass presence increases after planting. This is illustrated in the critical period figure developed for *E. globulus* and *H. lanatus* at this site (Figure 9.1). If grass re-establishment occurs soon after tree planting, competition for below-ground resources will occur early, while the young trees are in the vulnerable seedling stage (Nambiar 1990). In southern Australia it is common for grass to re-establish during the first spring/summer after planting at age four to six

months (Boomsma and Hunter 1990), therefore, the effects of competition can be strong. In this study, grass rapidly re-established in W treatments after planting, and it was clear that the young trees had a restricted opportunity to capture resources before the onset of competition. The weed curve (W) in Figure 9.1 shows that diameter growth declined immediately after planting in the presence of grass and that this decline was still apparent at age two years.

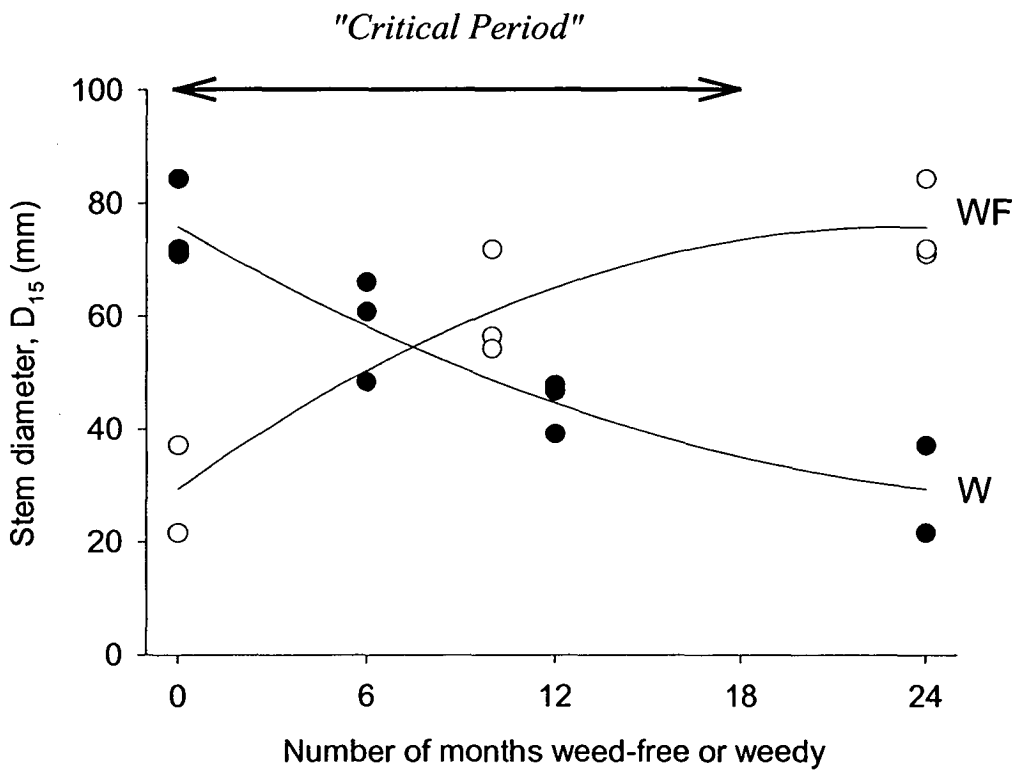


Figure 9.1 The critical period of *H. lanatus* competition with *E. globulus* based on stem diameter at 24 months (all receiving I_{Low} and N_{High}).

Where trees were ‘released’ from weeds after planting (eg. at age six and 12 months) tree growth recovery was slow (Figure 9.1), suggesting that suppressed trees had a reduced capacity to respond to improved conditions. Recovery was enhanced where

N-fertiliser was applied, with increased availability of N accessible to the suppressed trees. Factors associated with the slow recovery of 'released' trees would include: the restricted tree root systems with a reduced ability to capture N (and other nutrients) (Mitchell *et al.* 1999), immobilisation of mineral N by soil micro organisms, and leaching (Fisher and Binkley 2000). It was not until the second year of growth that a greater response to N-fertiliser occurred, which was associated with a more developed and extensive tree root system capable of increased nutrient capture. It appeared that *E. globulus* was not morphologically prepared for increased N availability (Lewty 1990, Mitchell *et al.* 1999) and although increased uptake occurred, trees could not rapidly translate this into growth.

This supports the theory that a morphological stage of growth is required before fast growth can be initiated (Kirongo *et al.* 2002) and was indicated by the decreasing height / diameter ratio of W trees receiving N-fertiliser compared to unfertilised treatments (Figure 4.3). It was probable that *E. globulus* in W treatments, was allocating more growth to roots than shoots, in an attempt to capture limiting soil resources (Goldberg and Fleetwood 1987). When soil mineral N concentrations increased due to N-fertiliser, increased uptake occurred, which led to an increased allocation to leaf area development and eventually, overall tree growth. As indicated by the results, this process was slow.

Where grass re-establishment was delayed (eg. WF6 where grass was sown six months after planting) there was a smaller impact on tree growth, which commenced from about age 10 months. By this time, the grass had developed into a sward and the trees had become well established due to a longer opportunity to capture site

resources in weed-free conditions. The weed-free curve (Figure 9.1) illustrates increasing *E. globulus* diameter growth with increasing duration of weed-free conditions. Maximum *E. globulus* growth was approached (80%) after approximately one year of weed control, while increased growth was obtained by extending control into the second year (20 months). This time was needed for the young trees to capture sufficient resources to sustain vigorous growth, and to develop a morphological and physiological condition, that was more tolerant of any grass re-establishment and associated competition after this time. The benefits of providing weed control into the second year of growth have been recognised by industrial plantation managers in southern Australia, where *E. globulus*, *E. nitens* and *P. radiata* are being established on ex-pasture sites (Stewart 1996, Adams and Dutkowski 1995, Fremlin and Misic 1999, Tomkins 2003).

9.3 *H. lanatus* – a vigorous competitor for soil mineral N

H. lanatus is a widespread, cool season perennial species capable of rapid development into a vigorous, dense grass sward, dominating the plant population. Growth at this site reflected seasonal and soil resource factors, with grass growth slowest in winter, strongest in spring, then flowering, maturity and seed set in early summer, followed by a period of dormancy, before autumn re-growth. This study indicates that growth was strongly dependant on mineral N availability. In the second spring after planting (age 13 months) N-fertilised grass contained four times the above-ground N content of unfertilised grass (310 and to 76 kg N ha⁻¹, respectively). Unfertilised grass displayed chlorosis, low vigour, and stunted shoot growth. It was clear that the growth of *H. lanatus* benefited proportionately more from available nutrients than young trees, consistent with many other studies, especially where

fertiliser was applied (Waring 1972, Squire 1977, Flinn *et al.* 1979, West 1984, Boomsma and Hunter 1990, Thevathavan *et al.* 2000).

The effect of *H. lanatus* on soil mineral N was strong, and during the first 18 months of tree growth, total mineral N was depleted by up to 70 %. Therefore, the availability of mineral N for capture by *E. globulus* was significantly reduced. Levels of depletion were such that mineral N approached the proposed critical concentration (0.05 mM) (Sands and Smethurst 1995) within eight months of planting. Tree responses to N-fertiliser occurred in spring, four months later. In experiment 2, the tree growth responses to N-fertiliser suggests that a critical value for NO_3^- in soil solution may be much higher than the 0.05 mM value proposed above, and may be closer to 3 – 4 mM (derived from Figure 7.6). This is because the method used by Sands and Smethurst (1995) was a hydroponic system, so there was good contact between the tree seedling root system and solution. Under field conditions, root depletion zones change with soil moisture content and an individual root of *E. globulus* may have a depletion zone around the root surface at a much lower concentration than in bulk soil solution. This highlights the importance of soil water content and its interaction with soil nutrient concentrations at the root surface under weedy conditions, compared to the bulk soil solution.

Mineral nitrogen (NH_4^+ and NO_3^-) is very dynamic in soil solution, with large fluctuations during the year, especially following N-fertiliser application. The differences in behaviour between NH_4^+ and NO_3^- in response to weed, fertiliser and irrigation treatments reflected their differences in transformation and mobility, and the influence of the sandy soil (low buffering capacity), seasonal changes in soil

water and temperature, leaching, and plant uptake. In addition, dilution due to high water content also played a role. It was therefore very difficult to manage concentrations of nutrients, especially in soil solution.

The strong growth response to weed control reflected the increased availability of soil water and nitrogen in these treatments and the lack of competition from weeds. In the WF treatments, the growth response of *E. globulus* to N-fertiliser was low despite the low nitrogen status of the sandy soil (Table 7.4) but is consistent with many other studies on ex-pasture sites, with early tree demand usually supplied from native mineralisation rates during the first one to two years of growth. The NO_3^- concentrations in soil solution were much higher than observed in forest soils (Smethurst 2000) and would have greatly exceeded demand by the young *E. globulus*. Large losses from leaching can also be a problem in these conditions (Smethurst and Nambiar 1989, Parfitt *et al.* 2003). Although NH_4^+ is the preferred form of N taken up by *E. globulus* (Shedley *et al.* 1995, Garnett 1996), the increased NO_3^- availability would also have been utilised along with the elevated NO_3^- concentrations in the groundwater at this site.

The application of N-fertiliser in WF treatments actually led to some suppression of tree growth and was associated with symptoms of copper and zinc deficiency. However, while high rates of N-fertiliser on sandy soils are known to induce micro-nutrient imbalances (Turnbull *et al.* 1994), the shallow water table and salinity of the irrigation water probably also contributed to this suppression. These factors, together with increasing intra-specific competition between trees in WF treatments, resulted

in a reduced expression of maximum growth differences between W and WF treatments at this site.

Foliar nitrogen concentrations in *E. globulus* reflected the strong competition for soil N in unfertilised W treatments. Deficiency levels (< 2%) were indicated from age five months, through to 18 – 20 months (Figure 8.3a). However, the N content and leaf mass of *E. globulus* in the same treatments indicated that significantly lower values continued to age 24 months, compared to WF trees. The foliar concentrations of P also indicated reduced levels in W compared to WF treatments but were not in the range considered to be deficient (Dell *et al.* 1995). However, the impact on growth at this site was not determined and the possibility of P deficiency could not be excluded. Similar results have been reported for young *Pinus elliottii* by Smethurst *et al.* (1993).

While foliar N concentrations indicated deficiency levels, only on one of several occasions during the two years was foliar N well correlated ($r^2=0.70$) with future growth. This occurred in well-watered weedy conditions in experiment 2 (Figure 8.10c) and indicated how increased N availability (from high rates of N-fertiliser) improved tree growth in the presence of weeds. However, in experiment 1 where there were contrasting weed, water and N-fertiliser treatments, the relationship between foliar N and diameter increment was weaker (eg. $r^2=0.51$). Therefore the utility of foliar N as an indicator of N deficiency in *E. globulus* growing under variable weed and water conditions may be limited.

Interpretation of foliar N status using N content and vector analysis, indicated that weedy and weed-free treatment differences persisted for a longer period (> 24 months) than that determined by foliar N concentration alone ie. 18 – 20 months. Vector analysis in particular, provided useful visualisation of treatment effects and trends in N status during the two-year study, which was improved even further by the inclusion of error bars in the vector diagrams (Figure 8.12). Another method, vector competition analysis (VCA), involving both the grass and trees together, provided further insight into the weed-tree interaction. Ratios of N content : biomass at age 10 and 13 months suggested that other factors in addition to N availability, were restricting growth of *E. globulus* in the presence of grass. Both water availability and P availability were implicated.

9.4 Competition for water

The ability of grasses to rapidly deplete soil water, especially in the surface soil is widely recognised (Nnyamah and Black 1977, Elliot and White 1987, Crunkilton *et al.* 1992, Johnson 1992, Palaez *et al.* 1992, Collet *et al.* 1996a, Dear *et al.* 1998). In young plantations, this commonly leads to weed-induced water stress, especially in Mediterranean climates, where water is the main limiting resource (Pereira *et al.* 1989, Boomsma and Hunter 1990, Richardson *et al.* 1993). Factors that determine the intensity, timing and duration of weed-induced tree water stress include: site water availability, evaporative demand, weed density and biomass (Momen *et al.* 1992), the age and development of the trees (Nambiar and Sands 1993) and the relative root volume occupied by each species (Aldrich and Kremer 1997).

In this study, the shallow water table in Blocks 1 and 2, provided ready access to moist soil for both species, therefore direct competition for soil water was probably only weak to moderate and short-lived (Figure 6.3). The strongest impact of grass on soil water availability occurred where the water table was >2 m in Block 3 and was exacerbated where grass growth was boosted by N-fertiliser (Figure 5.15). At age 13 months, grass depleted plant available water in the top 1m of soil by up to 80%. Depletion was associated with periods of moderate to high water stress in the young trees, especially during the first 13 months of growth. However, a trend suggested that stress declined with age, reflecting tree root development and increasing access to water at depth (Sands and Nambiar 1984).

At this site, high irrigation (I_{High}) on its own did not significantly improve tree growth in the presence of grass, reflecting the shallow water table. However, when I_{High} was applied in conjunction with N-fertiliser, the growth response by *E. globulus* increased compared to unfertilised treatments. This highlights the important influence of soil water content on nutrient availability and the implications for competitive interactions between plants. In the drier Block 3, responses to N-fertiliser were restricted not only because of water stress occurring in the first year but also because there was less soil water for transport of N to tree roots via mass flow or diffusion. Diffusion of NH_4^+ occurs over small distances (Carlyle 1986) compared to mass flow and therefore, restricted tree root systems, along with low soil water content would mean much reduced access to this resource. In Blocks 1 and 2, and with high irrigation, the higher soil water content probably increased N mineralisation and therefore the availability of mineral N, along with improving mass flow and diffusion (Nambiar *et al.* 1984, Berkowitz 1988, Comeau and

Spittlehouse 1992, Tinker and Nye 2000). However, it was difficult to show increased soil water content due to high irrigation at this site. It is therefore apparent that fluctuations of the mineral N concentrations in bulk soil solution do not adequately reflect changes in N concentrations and water content at the root surface, under weedy conditions.

While the requirement for effective control of grasses during establishment is generally well understood by industrial plantation growers, the success of farm forestry and Landcare projects has often been reduced due to lack of appreciation of this requirement. The importance of continued control to maximise survival and early growth is also poorly recognised in these sectors. Results from this study relate particularly to sites with high water availability (eg. high water tables). The increasing focus on tree-based amelioration (especially using eucalypts) of high water tables in Australia, needs to account for weed competition during plantation establishment. Rapid establishment of trees is essential for maximum leaf area development and to enhance canopy closure and site capture by the trees at the earliest stage. Sub-optimal weed management during establishment of such plantings will result in wastage of substantial human and financial resources targeted to this important rehabilitation effort. These principles particularly apply to the establishment of slower growing native trees and shrubs, where adequate weed control is also crucial.

9.5 Timing and duration of competition for soil water and nitrogen

Resource limitation (depletion of nitrogen and water) due to grass uptake, has been demonstrated in this study, providing strong evidence that competition between

H. lanatus and *E. globulus* has occurred (Keddy 1989). Competition was strongest and tree suppression greatest in the unfertilised W treatments, especially Block 3, where the combined effects of limiting water and nitrogen were greatest. This effect is consistent with many studies which suggest that below-ground competition is more important in infertile situations (Aerts 1999). It is commonly considered that competition for other soil resources such as soil nitrogen becomes more important after the first year, as trees access water at depth (Woods *et al.* 1992). However, this study has shown that competition for soil nitrogen is an important factor much earlier (occurring within three months of planting), and that it has been intimately involved with soil water availability.

Knowledge of the root distribution of competing plants is an important part of understanding species differences and the spatial and temporal overlap of rooting zones and resource requirements. It was clear that grass roots rapidly occupied most of the surface soil profile, and that lateral root development of young trees was severely restricted, an effect also observed by Smethurst *et al.* (1993) and Ludovici and Morris (1998). The dominance of grass root systems in surface soil, with root length densities usually much higher than young trees (Nambiar 1990, Tinker and Nye 2000), provides a competitive advantage for capture of soil nutrients and water (Aldrich and Kremer 1997, Nambiar and Sands 1993). This is a major determinant of competitive success of many grass species (Harper 1977, Morris *et al.* 1993, Robinson *et al.* 2001). In addition, the grass roots would be the first to be warmed in spring with increasing soil temperatures, along with being the first to receive water and nutrients (eg. from N-fertiliser application). Observations in the pot experiment (Chapter 4, Figure 4.2) showed that tree roots were intimately 'intertwined' among

the grass roots, had many hairs, but were not branched, suggesting a direct response to low mineral N concentrations in the presence of grass.

9.6 Predicting competitive effects at other sites

The interactions between soil water and nitrogen availability, and the timing and duration of competition at this site, provide an insight into the behaviour of these factors at other sites. On water-limited sites, competition for water will predominate, while on wetter sites, competition for nutrients such as nitrogen will dominate. The timing and duration of interaction and overlap of competition for both these resources depends on their respective levels of availability and the ability of the weed and tree species to affect these. A conceptual diagram of the intensity, timing and duration of competition for water and nitrogen between grass and young *E. globulus* is provided in Figure 9.2. This figure illustrates competition for soil water and nitrogen during the first two years, for four combinations of soil water and nitrogen availability (four ex-pasture ‘site types’). The Y-axis represents increasing strength or intensity of competition, while the X-axis indicates the duration (months) of the competition for soil water or nitrogen in each site type. It is assumed that grass re-establishment commences immediately after trees are planted.

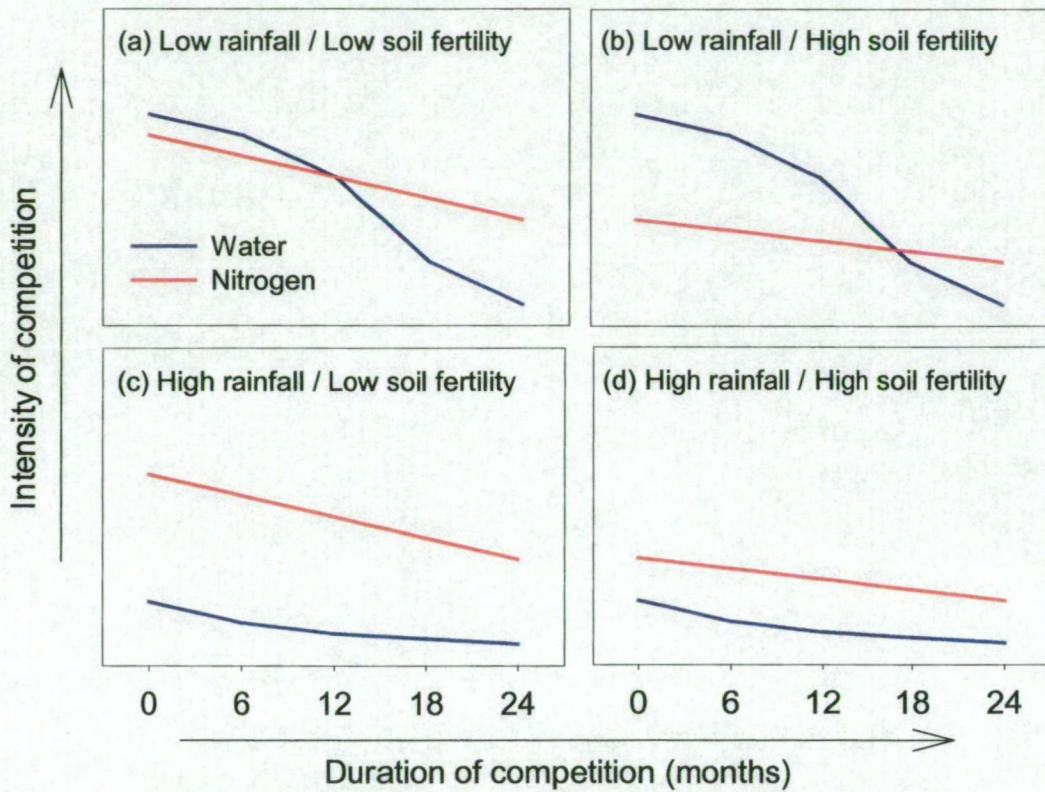


Figure 9.2 Conceptual diagram of the intensity, timing and duration of competition for soil water and nitrogen on a range of ex-pasture 'site types' It is assumed that grass re-establishment commenced immediately following tree planting.

On sites with relatively low soil water availability (eg. due to summer soil water deficit), and low soil nitrogen availability (eg. sandy soil), competition for both water and nitrogen would be high and occur early in the interaction between the two species (Figure 9.2a). By the second year, tree root growth should have access to deeper soil water, beyond the grass 'zone of influence' and direct competition for water would decline during this time. Competition for nitrogen could also be declining over time as the trees gradually develop, however the low soil nitrogen availability means that significant competition for nitrogen could continue beyond the second year, probably until canopy closure and site dominance by the trees.

Therefore, competition at this site type would be relatively long, extending into, and possibly beyond the second year, with both grass and tree growth affected by these limiting resources.

An example of a site like this would be a 'poor' pasture on a sandy soil and is consistent with results in the $I_{\text{Low}} N_{\text{Zero}} W$ treatment in Block 3. On sites of this type, re-establishing grass will have a longer opportunity to develop and impact on tree survival and growth. Suppression of tree growth and mortality will be high if weed control is not carried out for a sufficient duration to ensure trees get adequate access to the site resources. Extended grass presence can also occur when slow growing tree species are planted, or where trees are widely spaced (eg. silvopastoral management) (Hadryanto 1994, Clinton and Mead 1994b, Kellas *et al.* 1995, Lucot *et al.* 1998).

Figure 9.2b illustrates where competition for water dominates the competitive interaction on a site where water is limited but mineral N is not. Here it is suggested that competition for soil nitrogen is relatively lower and less important until the second year of growth. Suppression of tree growth in the presence of weeds would be high, as grass growth is likely to be more vigorous due to improved nutrition, however, direct competition for soil N is likely to be lower. Water availability for mass flow and uptake would remain an issue. The duration of weed control required to relieve competition at such a site would extend into the second year of growth. This scenario was also reflected in Block 3 in the $I_{\text{Low}} N_{\text{High}} W$ treatment.

On sites where there is high water availability but low soil nitrogen status, direct competition for water would be low while competition for N would be high (Figure

9.2c). In the presence of a shallow water table, N availability, more than water, would affect the competitive interactions between *H. lanatus* and *E. globulus* where low N mineralisation rates and reduced N availability would limit early growth. Vigorous grass growth, would mean that competition for soil nitrogen will be strong and occur early (Neary *et al.* 1990). This type of interaction was indicated in Blocks 1 and 2 in this study, with clear differences in tree growth in N-fertilised weedy plots compared to unfertilised plots. The duration of weed control required in this situation would also extend into the second year.

Figure 9.2d illustrates the timing and duration of competition for soil water and N on a ‘resource rich’ site. Such sites include those with a high water table or high reliable rainfall, and a fertile soil / good fertiliser history. Effluent-irrigated plantations are also an example of this ‘site type’ with high water and nutrient unputs. On such sites direct competition for soil water would be low. In contrast, the rapid grass growth, with dense root systems and a high demand and uptake of mineral N, means that significant competition for N would occur. Robinson *et al.* (2002) found that as N supply increased, grass acquisition of mineral N also increased, a situation exacerbated by the limited capacity of young tree roots to capture mineral N in comparison to the competing grasses.

On sites represented in Figure 9.2d the duration of weed control required to promote early growth of the trees, and site dominance, would be shorter than the other three ‘site types’ (ie. < 12 months duration). This is because sufficient site resources in weed-free conditions could support fast early growth of the eucalypts leading to earlier site dominance. However, this is also dependent upon stocking level and time

until canopy closure. Very rapid growth rates in weed-free conditions can however lead to undesirable outcomes, such as induced micronutrient deficiencies and poor tree form (eg. stem distortion). Such factors need to be considered when implementing a weed management program.

The interaction between above- and below-ground competition and resource availability, is an important consideration in the study of plant competition (Casper and Jackson 1997, Tinker and Nye 2000, Robinson *et al.* 2002). A study on the interaction between *H. lanatus* and *A. vulgaris* (Nielsen 1998) showed that a major competitive mechanism was competition for light between the two species, which was associated with dominant shoot growth of the grass, particularly in N-fertilised treatments. Such interactions commonly result in reduced botanical diversity, especially on fertile sites (Harper 1977, Tilman 1990, Turkington 1990). The risk of competition for light between grass and young trees is also high during the early stages of growth, when the trees are small and easily over-topped (Harper 1977, Caldwell *et al.* 1995, Casper and Jackson 1997). Robinson *et al.* (2002) demonstrated the interrelation between soil N availability and competition for light between a boreal grass, *Calamagrostis canadensis* and young jack pine (*P. elliotii*). As soil N availability increased, above-ground biomass of the grass increased, which led to increasing competition for light. In contrast, Jack pine above-ground biomass, N content and photosynthetic rate, decreased as N availability increased. This is consistent with Wilson and Tilman (1995) where the competitive response with respect to root and shoot competition varies as a function of N availability. The application of N-fertiliser can exacerbate competition for light where grass weeds are present (Flinn *et al.* 1979, Boomsma and Hunter 1990). Over-topping and

competition for light was not a factor in the present study because timely and effective slashing around young *E. globulus* seedlings was carried out.

However, improved microclimatic effects could also be an important factor contributing to the improved growth in WF treatments compared to W treatments. Examples that have been discussed include increased soil temperature, especially during the early growing season, and the possibility of increased light and heat reflectance from the light sandy soil in WF treatments. These microclimatic effects require further investigation. Another factor that should not be discounted in the plant – plant interactions is allelopathy. While very difficult to demonstrate the presence of this mechanism, it is also very difficult to separate it from resource competition.

9.7 Conclusions

While many studies of plant competition in forests suggest or indicate which resource is limiting growth, few report on the timing, duration or importance of the competition, or the presence of interacting factors / stressors. This study has highlighted the interacting effects of weed control and the availability of soil water and nitrogen; the time of weed presence relative to tree planting; and the individual effect on, and response to, site resources by both trees and weeds (Zimdahl 1988, Goldberg 1996, Robinson *et al.* 2001). In conjunction with critical period analysis, this has contributed to an improved understanding of the competitive processes between *H. lanatus* and young *E. globulus* at this site. These factors can also be used as a basis for predicting the nature, timing and duration of weed competition at other sites, and therefore, the critical period of weed control. Therefore, the opportunity for

increasing the effectiveness and efficiency of grass control through improved timing and duration of control, specific to each situation, is possible.

The competitive mechanism at this site has been primarily associated with depletion of soil resources such as mineral N by the grass, driven by the high demand for N and facilitated by dense root systems that dominated the surface soil. The result was reduced mineral N availability for uptake by the young suppressed trees, which was further limited by their restricted root systems. Where soil water is readily available, competition for N will be stronger and of greater importance than competition for water, whereas under drier conditions competition for both water and N will occur. The importance of water for transport of nutrients to the restricted tree root systems has been highlighted.

The competitive effects of the grass could not be fully compensated even with high rates of N-fertiliser. There was slow recovery of trees from a suppressed state in weedy conditions and a sufficient period of adjustment was required, before the young trees were morphologically and physiologically prepared for the increased resource availability, and vigorous growth.

Weed-free conditions allow the young trees to capture site resources necessary for fast early growth, and where *E. globulus* is being established on ex-pasture sites, weed control should extend from planting through the first 12 months of growth. If the site is 'resource poor' then weed control would need to be extended into the second year.

9.8 Future research

Our understanding of competition for site resources has been improved by this study at the Penna site. However, there is a need to expand the study and extend the range of sites examined (with varying soil water and nitrogen status) so that our predictive ability on the timing, duration and intensity of competition on ex-pasture sites can be further improved. Validation of the predicted competitive interactions for soil water and nitrogen at the four simulated site types (Figure 9.2) is required with field experiments located at two to three representative sites. This includes investigation on clay soils (contrasting with the sandy topsoil at Penna), to determine the competitive interactions for soil water and nutrients. Further work is also required under controlled conditions eg. glasshouse studies of detailed below ground processes, and use of process-based models.

It is also important that adequate site investigation and characterisation is carried out of potential experimental sites, so that treatments are not compromised by site factors such as a shallow or perched water table. It would be useful to have replication of treatments over a period of three years at each selected site, so that climate variations (eg. drought incidence) can be accounted for. Changes in key resource parameters (spatially and temporally) need to be determined at each site eg. soil water content, and soil solution concentrations, along with key plant parameters eg. root length density and biomass.

Field studies need to include a close linkage between physiological measurements (both trees and weeds) and their responses to soil water and nutrients, with key parameters selected. The effect of low nutrient, or water status on physiological

processes such as photosynthesis should provide a clearer understanding of the timing and duration of sensitivity and degree of plant responses to changing resource levels. These can then be used for inputs into process-based models eg. CABALA (Battaglia *et al.* 2004) to improve understanding and predictions of the interactions. In addition, further knowledge gaps can be identified.

Key parameters from each field experiment are also necessary for detailed studies under controlled conditions eg. glasshouse studies. However, such studies are constrained by pot size and are normally restricted to tree seedlings aged less than 12 – 18 months old (for fast growing eucalypts). Glasshouse studies are suitable for detailed study of root interactions between grass and young tree seedlings and could quantify rates of root growth and extension, occupation of space and the interaction between species under contrasting levels of resource availability. The use of larger pots / containers is possible and has been successfully carried out with young *Quercus petraea* and grasses (Collet *et al.* 1996b). The stocking level used in this study was high (1600 stem ha⁻¹) compared to the industry standard (1000 – 1400 stems ha⁻¹). The impact of the wider espacement on the timing of canopy closure needs to be determined.

The interaction of water and nitrogen was important at this site, and has been difficult to demonstrate at the resource level in the field. This would be better suited to glasshouse studies. The effect of soil water content at the root surface and root zone on nitrogen uptake is an important area requiring further research. Critical nitrogen concentrations derived from hydroponic studies, simulating bulk soil solution (Sands and Smethurst 1995) do not adequately reflect these conditions.

Linkages are required between models that relate water and nutrient supply (Tinker and Nye 2000) to models that predict root growth, including eucalypt and grass root density and distribution during plantation development. In addition, the spatial variation in root demand for soil water and nutrients needs to be accounted for.

Other factors that may be involved in the competitive interaction between young trees and grass need more detailed monitoring eg. microclimate effects such as air and soil temperature with linkages to physiological responses above and below ground and soil processes such as N-mineralisation. There is also a need to quantify the amount of light reflectance (reflection coefficient) from the surface soil compared to a vigorous grass sward and relate this to a microclimatic enhancement of tree growth in weed control studies.

Nitrogen and phosphorous have been the main plant nutrients investigated in this study, which in the case of nitrogen, accounted for much of the outcome of the competition. Along with closer linkage with tree and weed physiology, a more comprehensive investigation of other nutrients such as potassium is also required. More work is required using Vector Competition Analysis to understand competitive interactions between trees and weeds. The use of tree crown biomass data rather than leaf weight may be more informative.

The critical period method has been useful in this study however, further use at other sites should involve tighter critical period intervals (eg. three monthly), along with improved grass establishment, so that clearer definition of the curves is possible. This may be important for other species such as *E. nitens* or *P. radiata*. The latter

species is generally slower growing than eucalypts during the initial four to five years of growth. Time of planting may also need to be accounted for, with winter, spring and autumn treatments. The timing of weed emergence, growth and dynamics relative to time of tree planting is a very important factor in competitive interactions and is also related to the timing of site preparation such as cultivation.

A useful line of inquiry would be to determine why high N-fertiliser application did not fully compensate for the high competitive pressure exerted by grasses on the young *E. globulus*. Increased N availability can overcome some of the competitive effects but high rates of fertiliser are required. Much lower (and economic) rates of fertiliser application may be possible if methods for channelling fertiliser to the trees, while avoiding access by grass, can be developed.

This research has shown the optimal timing and duration of weed control in young *E. globulus* which maximises early growth while minimising the risk of significant resource competition between grasses and the young trees. Analysis is required to extend this to include the optimal economic timing and duration of weed control. This analysis needs to account for the cost of growth losses due to delaying the application of weed control or shortening its duration; the cost of applying successful weed control, and the positive growth responses that may occur over the rotation.

10. Implications for establishment of *E. globulus* on ex-pasture sites

***H. lanatus* causes strong suppression of tree growth**

Where grass weeds occur during tree establishment, significant growth losses due to competition for soil water and nitrogen can occur. Consequently, survival, height and diameter growth of trees can be significantly reduced compared to weed-free conditions and result in greatly reduced financial viability of a plantation investment.

Effective and timely control of grasses is essential

Where grasses dominate the weed population, *E. globulus* requires weed-free conditions for at least the first 12 months of growth. The interaction between soil water and nitrogen availability at a given site has a strong influence on the intensity and duration of competition between grass and young *E. globulus*, and therefore the requirement for control to be extended beyond the first year of growth. Early weeds are considered to be the most damaging and as found in this study, early and sustained weed control is required until site dominance by the tree crop occurs.

If weed control is delayed until after planting, the longer the delay, the greater the impact of weeds on tree survival and early growth. In addition, the young trees will take longer to respond.

If weed control is delayed, release during the first spring is important

In southern Australia, where *E. globulus* is generally planted during winter and early spring, achieving adequate weed control during the first spring and summer after planting is very important. In spring, increasing resource availability (water and

nutrients) coupled with enhanced growing conditions (air and soil temperature and light intensity) are conducive to vigorous development and growth of the young trees. Any depletion of resource availability at this time by grasses reduces such growth potential.

Trees recover slowly after ‘release’ from established grasses

When trees are ‘released’ from grasses after planting, growth responses can be delayed for three to six months, depending upon the amount of grass present at the time, the timing of weed control and soil fertility status. It is during this period that the trees adjust physiologically and morphologically to a stage where they are capable of responding to increased availability of resources.

Residual control of grasses is required

A single weed control treatment (eg. cultivation, hand weeding or glyphosate application) does not provide weed-free conditions of sufficient duration for optimum growth of young *E. globulus* and rapid re-invasion of a weed-free zone by grass commonly occurs. *E. globulus* growing with vigorous grasses such as *H. lanatus* will require weed-free conditions for a longer period than these one-off treatments can supply.

The success of farm forestry and Landcare projects have often suffered because the requirement for effective management of grasses during establishment is not fully appreciated. This is particularly important for the establishment of slower growing native species and shrubs.

Fertilising weedy sites feeds the weeds

Vigorous grasses like *H. lanatus* can capture most of the applied N-fertiliser at the expense of the young trees and growth. In addition, above-ground growth of the grasses can cause competition for light. Despite the shallow water table and the application of high rates of nitrogen fertiliser, the competitive effects of the grass could not be totally compensated.

On low fertility sites, strategically placed fertiliser soon after planting to boost early tree growth before grasses become re-established, can be an important part of weed management.

Good prospects for the future

The interaction between soil water and nitrogen availability at a given site has a strong influence on the intensity and duration of competition between grass and young *E. globulus*, and therefore the requirement for control to be extended beyond the first year of growth. It is possible to predict these interactions, within broad classes, and thus the timing and duration of weed control required. This requires a good understanding of site factors, soil water and nutrient availability, species characteristics, and the ability to differentiate between sites

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